# State of Washington Water Research Center Annual Technical Report FY 2009

# Introduction

The overall strategic mission of the State of Washington Water Research Center (SWWRC) is to: i) facilitate, coordinate, conduct, and administer water-related research important to the State of Washington and the region, ii) educate and train engineers, scientists, and other professionals through participation in research and outreach projects, and iii) disseminate information on water-related issues through technical publications, newsletters, reports, sponsorship of seminars, workshops, conferences as well as other outreach and educational activities.

The SWWRC has developed a multi-faceted, interdisciplinary approach to accomplish these goals. To promote research and outreach, the SWWRC has been organized into five program areas: Watershed Management, Groundwater Systems, Environmental Limnology, Vadose Zone Processes, and Outreach and Education. These programs have helped prepare several multidisciplinary research proposals and provide better links between faculty and the SWWRC. These are in addition to the Director's primary research interests in surface-groundwater interaction, remote sensing, and storm water. The Center is also heavily involved in international research and education activities.

Lessons learned from the research and outreach components are disseminated to faculty and stakeholders and used by the Director to shape and enhance the education goal. Research projects are also used as a mechanism to fund graduate and undergraduate students.

The SWWRC is continuing its intensive efforts to reach out to agencies, organizations, and faculty throughout the State. Activities include presentations to watershed groups, participation in regional water quality meetings, and personal contacts. A dynamic web page has been created and is continually updated to share information with stakeholders.

It is within this overall context that the USGS-funded project activities reported in this document must be inserted. These include the internally funded projects as well as the national proposals awarded to the Center. These projects provide a solid core to the diverse efforts of the SWWRC. Water quantity and quality issues continue to be a major concern in the State of Washington due to the endangered species act, population growth, industrial requirements, and agricultural activities. Emerging issues such as water resources management in the face of global warming, water reuse, energy-related water quantity and quality considerations, ecological water demands, and storm water runoff regulations are also beginning to raise concerns. All of these issues will be important drivers of the activities of the SWWRC in the foreseeable future.

# Research Program Introduction

In accordance with its mission, the SWWRC facilitates, coordinates, conducts, and administers water-related research important to the State of Washington and the region. Research priorities for the State of Washington are established by a Joint Scientific Committee which includes representatives from water resource professionals at state agencies, universities, and the local USGS office. The Center supports competitively awarded internal (within the State of Washington) grants involving water projects evaluated by the Joint Scientific Committee. The Center also actively seeks multidisciplinary research at local, state, and national levels. Meetings between stakeholder groups, potential funding agencies, and research faculty are arranged as opportunities arise. Faculty are notified of any opportunities for individual or collaborative endeavors. The Center also submits proposals on its own behalf.

During FY 2009, three local research projects were selected for funding by the Center: (1) Adaptive Management of Mountain Forests to Prevent Mass Wasting under Climate Change was granted to Dr. Jenny Adam, (2) Understanding Controls on Cyanobacteria Blooms: Vancouver Lake as a Model System was awarded to Dr. Gretchen Rollwagen-Bollens, and (3) Influence of Large Wood Addition on Nitrogen Transformations at the Surface Water/Ground Water Interface was given to Dr. Clay Arango. As described below, these projects address important state issues but are also relevant to national interests.

A national project granted to the University of Washington was run through the SWWRC during this accounting period. The project, West-Wide Drought Forecasting System: A Scientific Foundation for National Integrated Drought Information System (NIDIS) was granted to Dr. Anne Steinemann. A progress update of this project is also presented in this document.

# West-Wide Drought Forecasting System: A Scientific Foundation for NIDIS

## Basic Information

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|---|---|
| **Title:** | West-Wide Drought Forecasting System: A Scientific Foundation for NIDIS |
| **Project Number:** | 2006WA180G |
| **Start Date:** | 9/1/2006 |
| **End Date:** | 8/31/2010 |
| **Funding Source:** | 104G |
| **Congressional District:** | 7 |
| **Research Category:** | Climate and Hydrologic Processes |
| **Focus Category:** | Drought, Hydrology, Management and Planning |
| **Descriptors:** | Drought Forecast, Drought Mitigation |
| **Principal Investigators:** | Anne Steinemann, Dennis Lettenmaier, Andrew Wood |

## Publications


1. Steinemann, Anne C., 2007, Using Climate Forecasts for Drought Management, Oral Presentation at the 5th Annual NOAA Climate Prediction Applications Science Workshop , Seattle, Washington. March 20-23, 2007.
2. Rosenberg, E., Andrew W. Wood, Q. Tang, Anne C. Steinemann, B. Imam, S. Sorooshian, and Dennis P. Lettenmaier, 2007, Improving Water Resources Management in the Western United States through Use of Remote Sensing Data and Seasonal Climate Forecasts, Poster Presentation at the 5th Annual Climate Prediction Applications Science Workshop, Seattle, Washington, March 20-23, 2007.
3. Shukla, S., D. Alexander, A. Steinemann, and A. W. Wood, 2007, Applications of Medium Range To Seasonal/Interannual Climate Forecasts For Water Resources Management in the Yakima River Basin of Washington State, Poster Presentation at the 5th Annual Climate Prediction Applications Science Workshop, Seattle, Washington, March 20-23, 2007.
4. Lettenmaier, Dennis P., Andrew W. Wood and Kostas Andreadis, 2006, A System for Real-time Prediction of Hydrological and Agricultural Drought over the Continental U.S., EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 87(52): Abstract GC31A-07.
5. Fontaine, Matthew M. and Anne C. Steinemann, 2007, Assessing and Mitigating Drought in Washington State, Poster Presentation at the 5th Annual NOAA Climate Prediction Applications Science Workshop, Seattle, Washington, March 20-23, 2007.
6. Shukla, S., D. Alexander, Anne C. Steinemann, and Andrew W. Wood, 2007, Applications of Medium Range To Seasonal/Interannual Climate Forecasts for Water Resources Management in the Yakima River Basin of Washington State, University of Washington Water Center Annual Review of Research, Seattle, Washington, February 14, 2007.
7. Wood, Andrew W., Anne C. Steinemann, D. Alexander,and S. Shukla, 2006, Applications of Medium Range to Seasonal/Interannual Climate Forecasts for Water Resources Management in the Yakima River Basin of Washington State, EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 87(52): Abstract H53C-0648.
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12. Shukla, S., and A.W. Wood, 2008, Use of a Standardized Runoff Index for Characterizing Hydrologic Drought, Geophysical Research Letters, 35(L02405), doi:10.1029/2007GL032487.
13. Wood, A. W., and J. C. Schaake, 2008, Correcting Errors in Streamflow Forecast Ensemble Mean and Spread, Journal of Hydrometeorology, 9(1): 132-148, doi:10.1175/2007JHM862.1.
14. Vano, J. A., and Anne C. Steinemann, 2007, Using Climate Forecast Information in Water Resource Planning: Opportunities and Challenges in the Yakima River Basin, Washington, USA, EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 88(52): Abstract H24A-05.
15. Wood, Andrew W., S. Shukla, J. A. Vano, and Anne C. Steinemann, 2007, Connecting Climate, Hydrologic and Drought Predictions to Water Resources Management in Washington State, EOS Transactions, American Geophysical Union, Fall Meeting Supplement 88(52): Abstract H23F-1678.
16. Andreadis, K., Dennis P. Lettenmaier, and Andrew W. Wood, 2007, Drought Identification and Recovery Prediction, Oral and Poster Presentations at the 5th Annual NOAA Climate Prediction Applications Science Workshop, Seattle, Washington. March 20-23, 2007.
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19. Vano, Julie A., 2007, Challenges and Rewards of Translating Climate Change Science for Non-scientists: Two Case Studies on Drought, Oral Presentation at the 2nd Annual Graduate Climate Conference University of Washington Charles L. Pack Forest Center, Washington. October 19-21, 2007.
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57. Fontaine, M., and A.C. Steinemann, 2008, Assessing vulnerability to natural hazards: An impact-based method and application to drought in Washington State, ASCE Natural Hazards Review (in press).
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62. Wang, A., T.J. Bohn, S.P. Mahanama, R.D. Koster, and D.P. Lettenmaier, 2008, Multimodel reconstruction of drought over the continental United States, Journal of Climate (submitted).
63. Wood, A.W., and J.C. Schaake, 2008, Correcting errors in streamflow forecast ensemble mean and spread, Journal of Hydrometeorology, 9(1): 132-148, doi:10.1175/2007JHM862.1.
64. Annual Review of Research, 2007, 2008, 2009, 2010. A symposium of water research hosted by the University of Washington Water Center, Anne Steinemann, Director, USGS research was featured at this event. Seattle, Washington. http://depts.washington.edu/cwws/.
65. Bohn, T., Feb. 2008. Drought and model consensus: Reconstructing and monitoring drought in the U.S. with multiple models, The Water Center Annual Review of Research. Seattle, Washington. http://depts.washington.edu/cwws/.
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# 1. PROBLEM AND RESEARCH OBJECTIVES

Drought is the costliest natural hazard in the U.S., averaging $6-8 billion in damages annually (FEMA, 2004). The 1988 central U.S. drought alone cost almost $62 billion (NCDC, 2006). Forecasts and real-time assessments of drought offer the potential to mitigate drought impacts. However, current drought monitoring systems for the western U.S. lack a predictive component for specific hydrologic indicators. Further, given that hydrologic impacts account for most drought losses, USGS data are essential to making drought forecasts useful.

In this research, we develop a drought forecast and nowcast system for the western U.S., which serves as a scientific framework for prediction and assessment of agricultural (soil moisture) and hydrologic (streamflow) drought in the region. This work, in collaboration with USGS personnel, will provide early warning capabilities and science-based indicators that are critical for the National Integrated Drought Information System (NIDIS), an effort of the Western Governors' Association (WGA), the National Drought Mitigation Center (NDMC), NOAA, the USGS, and other agencies. Our work also contributes to the U.S. Drought Monitor, which currently uses our National Surface Water Monitor, by incorporating USGS data into methods to characterize and forecast drought conditions, persistence, and recovery. Further, the PIs and their students are working directly with water managers in selected states in the region (Washington, California, and others) to apply this forecast system to water resources decisions.

Our drought forecasting system builds upon the University of Washington's operational West-Wide Hydrologic Forecast System and National Surface Water Monitor. In doing so, we extend the Variable Infiltration Capacity (VIC) macroscale hydrology model to utilize, via data assimilation methods, USGS hydrologic data in ways not currently exploited by prominent drought information services, such as the U.S. Drought Monitor.

Our specific objectives are to (1) implement a version of the VIC model that represents near-surface groundwater directly and thus can incorporate USGS well level data; (2) assimilate observations not presently used in the West-Wide system that are highly relevant to drought, such as USGS streamflow data from HCDN and similar stations, soil moisture information, and USGS well data; (3) produce probabilistic forecasts of drought persistence and recovery using ensemble prediction methods that incorporate climate forecasts out to one year; and (4) work with the WGA, the NDMC, and other users, such as state water agencies, to incorporate the resulting drought forecasts and nowcasts into drought information systems and water management decisions.

In addition to interactions with the WGA and the NDMC, we are working closely with Dr. Randall Hanson and Dr. Michael Dettinger of the USGS California Water Science Center in San Diego. Specifically, we work with Drs. Hanson and Dettinger in (1) testing VIC predictions of well level anomalies at selected locations in California, (2) development of algorithms for assimilation of USGS well level and streamflow data, as well as other hydrologic data, into the drought forecasting system, (3) obtaining retrospective and real-time hydrologic data, and (4) validation of drought nowcasts and forecasts across the western U.S. study domain.

## 2. METHODOLOGY

The overall goal of the proposed project is to develop a drought forecast and nowcast system for the western U.S. (which we define as the continental U.S. west of the Mississippi River), which serves as a scientific framework for assessment and prediction of agricultural (soil moisture), and hydrologic (streamflow) drought in the region, and as the scientific core of NIDIS. The system leverages the existing University of Washington WHFS and SWM. Our specific objectives are as follows:

(1) To implement a version of the VIC model that represents near-surface groundwater (water table) directly, based on a simple groundwater model of Niu et al. (2007). This model will be capable of incorporating USGS well level observations via data assimilation in areas where there is strong connectivity between groundwater and surface water systems;

(2) To develop procedures for assimilating observations that are not presently incorporated in the WHFS but are highly relevant to drought, such as USGS well data, USGS streamflow data from HCDN and similar stations not greatly affected by water management, and soil moisture from such sources as the NRCS SCAN network and state networks where such data are available;

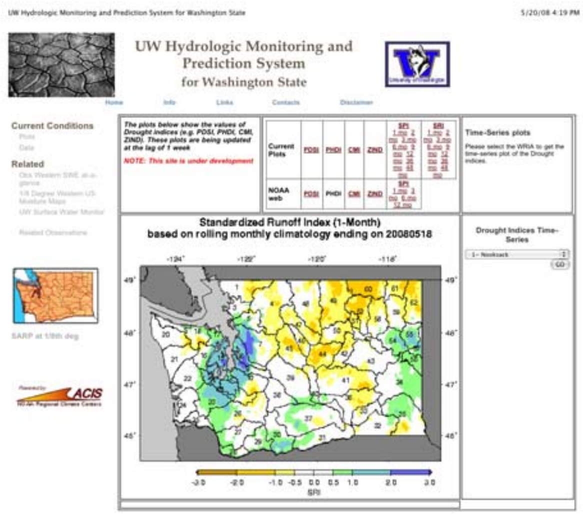
(3) To develop methods for producing probabilistic forecasts of drought persistence and recovery, using ensemble prediction methods that incorporate official NOAA CPC ensemble climate forecasts for lead times out to one year; and

(4) To work with the NDMC, the WGA, and other users (primarily state agencies in the western U.S.) to incorporate the resulting drought nowcasts and forecasts into water management decisions and into drought information systems such as the Drought Monitor/Outlook and NIDIS.

## 3. PRINCIPAL FINDINGS AND SIGNIFICANCE

A Washington statewide drought monitoring system has been implemented using the VIC hydrologic model at 1/16 degree (about 6 km grid mesh). This system provides real-time, daily updating analyses (maps, datasets, and time series of hydrologic variables) that characterize hydrologic conditions throughout the state, presented via a website (http://www.hydro.washington.edu/forecast/sarp/). It also presents a weekly update of the current drought status in terms of drought indices, including Palmer Drought Severity Index (PDSI), Palmer Hydrologic Drought Index (PHDI), Crop Moisture Index (CMI), and Z Index (ZIND), as well as a daily update of 1, 2, 3, 6, 9, 12, 24, and 36 month averaged values of Standardized Precipitation Index (SPI) and Standardized Runoff Index (SRI). Work has begun to prepare the statewide monitoring system with an embedded focus region of the Yakima River Basin as the initializing state for 2 week to 1 year lead hydrologic forecasts, from which it will be possible to obtain drought onset and recovery predictions. These will be based on both ensemble streamflow prediction (ESP) techniques advanced by the National Weather Service, and NCEP Climate Prediction Center seasonal outlooks. To this end, the Climate Prediction Center's new consolidated forecast (not previously available to the public) has been obtained and is being evaluated in the Washington State domain. In addition, preliminary work to develop methods for forecast error reduction has resulted in a published paper (Wood and Schaake, 2008).

To supplement existing drought characterization methods, we developed a method known as the standardized runoff index (SRI), which is calculated as the unit standard normal deviate associated with the percentile of hydrologic runoff accumulated over a specific duration. This method is similar to the standardized precipitation index (SPI), but relates to a hydrologic variable, runoff, rather than a climatic variable, precipitation. Such an approach better accounts for the effects of seasonal lags in hydrologic response to climatology. For example, SPI does not account for the effects of decreased snowmelt on summer conditions. Maps of SPI and SRI, based on a rolling climatology, are updated daily for the continental U.S. at ½ degree spatial resolution as part of the U.W. Surface Water Monitor (Figure 1, http://www.hydro.washington.edu/forecast/monitor/indices/index.shtml). The development of this index and its comparison with SPI are presented in a published paper (Shukla and Wood, 2008).




We have met with key stakeholders (e.g. federal, state, and regional water officials, irrigation district managers, farmers) in the Yakima River Basin, Washington, to assess their needs. We discussed current organizational decision processes, current uses of forecast information, needs for NOAA forecast products, barriers to forecast use, and potential net benefits of using the NOAA-CPC forecasts and the drought forecast information developed by this project. In this process, we identified four decision-making realms: (1) filling reservoirs without flooding in winter and spring; (2) maintaining flows for fish in fall; (3) week-to-week operations in summer; and (4) agricultural decisions in winter for irrigation season. The relevant decision timing relative to forecast timing for each of these operational periods were also assessed (Figure 2).

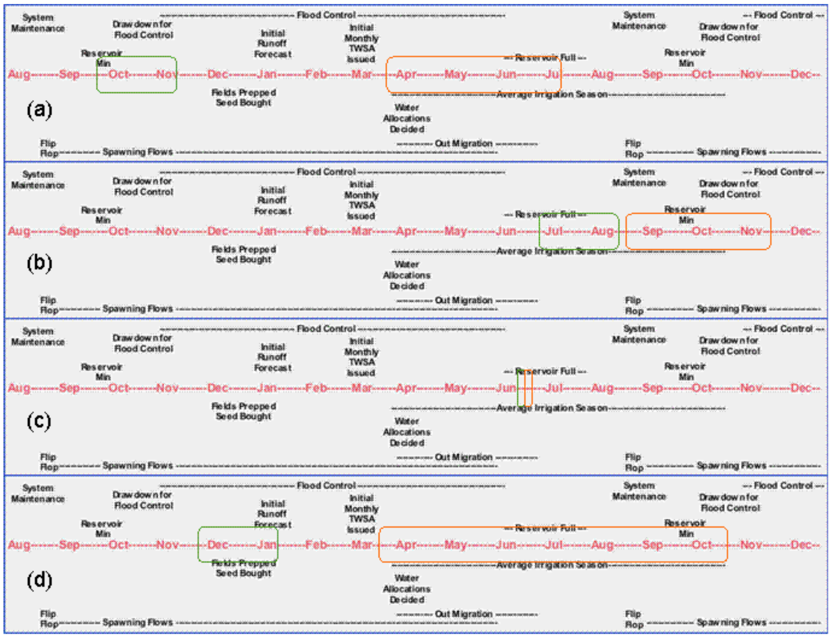



Figure 2. Four identified decision-making realms, with green circles around period in which decisions are made and orange circles around the relevant time of forecast. (a) Filling reservoirs without flooding in winter and spring, (b) maintaining flows for fish in fall, (c) week-to-week operations in summer, and (d) agricultural decisions in winter for irrigation season.

We have implemented and tested a drought recovery strategy, based on initializing VIC with current (soil moisture) conditions, and running forward in time with ensembles of future climate conditions. Maps of median forecast percentile and the forecast probability of conditions below the 20$^{th}$ percentile for soil moisture, SWE, and cumulative runoff for the continental United States are available at [http://www.hydro.washington.edu/forecast/monitor/outlook/index.shtml](http://www.hydro.washington.edu/forecast/monitor/outlook/index.shtml). Ensemble Streamflow Prediction (ESP)-based and CPC outlook-based forecasts of daily streamflow volumes are made near the beginning of each month. These outputs are summarized as monthly hydrograph distribution plots available for several forecasting stations in the west-wide U.S. Region (Figure 3, http://www.hydro.washington.edu/forecast/westwide/sflow/). The ESP ensembles are drawn from sequences of past observations, whereas the CPC outlook ensembles are derived from the CPC's probability of exceedance (POE) forecasts for average monthly temperature and total precipitation in each of 102 climate divisions within the US. Probabilistic outcomes will be compared with nominal conditions (as simulated with the VIC model using the true forcings) for the retrospective period, and maps of the accuracy of climate recovery predictions will be produced as a function of season and lead-time. Figure 4 compares the ensembles of

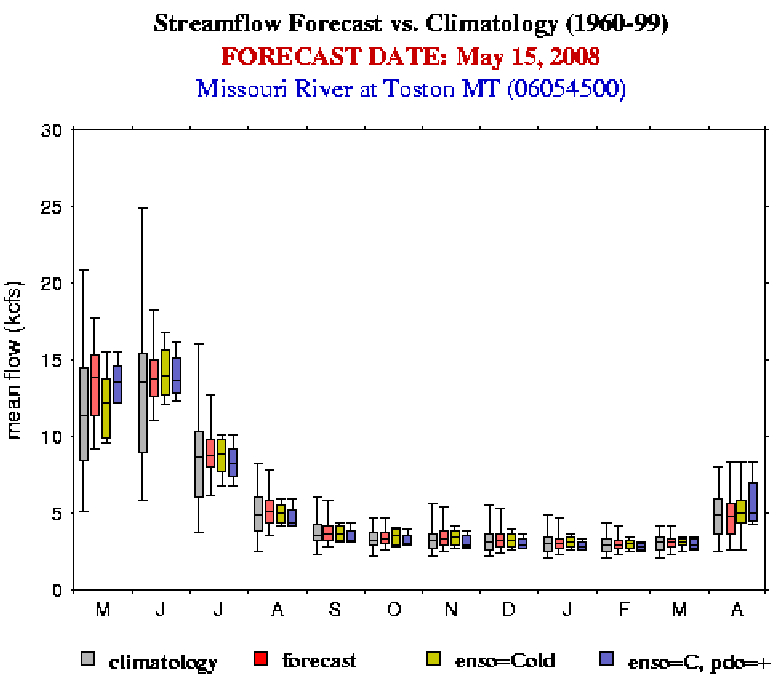



Figure 3. ESP forecast for mean monthly streamflow on the Missouri River at Toston, MT, as of May 15, 2008.

predicted soil moisture, averaged over the Arizona-California portion of the drought, compared with "actual" (real-time) model soil moisture over the 6-month forecast period.

We have also implemented a drought nowcast system in real-time, and are in the process of implementing a drought forecasting system over the western U.S. domain, using methods similar to those illustrated in Figures 3 and 4, at one-quarter degree spatial resolution (our current Surface Water Monitor uses one-half degree resolution). We have recently implemented a drought identification system at the SW Monitor native ½ degree resolution. We summarize the method below.

The VIC hydrologic model produces near real-time, spatially and temporally continuous fields of drought-related variables such as soil moisture and streamflow (we focus here on soil moisture). Drought is defined locally at each model pixel using a thresholding method, i.e., whenever soil moisture or runoff are below a certain threshold value the pixel is classified as being "in drought". Instead of using the absolute values of soil moisture (or runoff), droughts are identified by expressing each pixel's soil moisture as percentiles of their 1915-2004 respective model climatology. This essentially normalizes the soil moisture and runoff time series to range of 0 to 1 across the domain. The threshold chosen here is 0.2, which corresponds to severe drought, with severity being calculated as the percentage remainder of the subtraction of the soil moisture (or runoff) percentile from unity.

Soil moisture and runoff spatial fields are estimated and used to produce weekly maps, which are then used in the drought identification procedure. In order to keep a certain temporal continuity in the areas identified as drought from one time step to the next, we have to apply some kind of temporal persistence constraint. This ensures that areas are classified as drought recovered relatively consistently, given that this is a near real-time application. Drought transition probabilities (probability that a pixel will recover if it was in drought the previous 1, 2 or 3 weeks) were calculated from the model climatology. These are then used after the first stage of drought identification (any pixel below the 20th percentile is classified as drought) to retain the temporal persistence in drought areas. The recovery probability threshold is set to 50%, but this can be adjusted accordingly.

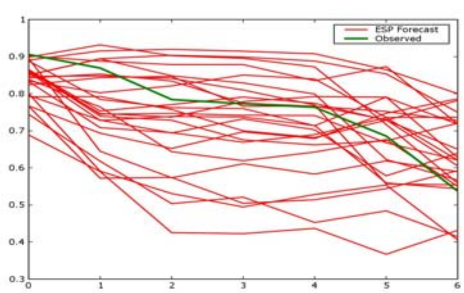



Figure 4: Spatial average soil moisture over AZ-CA starting on Feb. 1, 2006, and progressing through August, as compared with "actual" soil moisture (real-time model estimates).

The algorithm continues by applying a spatial median filter using a 5x5 window, in order to attain some spatial smoothing by minimally distorting the actual percentile values. The initial partitioning of the image then follows, by grouping adjacent pixels that are in drought into clusters. This fragmented image is then adjusted by merging clusters that are sufficiently close in terms of distance, and eliminating drought clusters that occupy less than the area of 20 model pixels. The final step includes the reclassification of pixels that are within larger drought areas as being in drought, by examining the neighborhood of each pixel not in drought within a radius of 3 model pixels. This procedure results in a map of drought areas, and also allows for their consistent tracking through time. Figure 5 shows results of application of the method over the continental U.S. starting in early May, 2007, as droughts were evolving in both the southeastern and southwestern U.S., and proceeding through the first week in June, 2007. The spatial limits of drought are updated once per

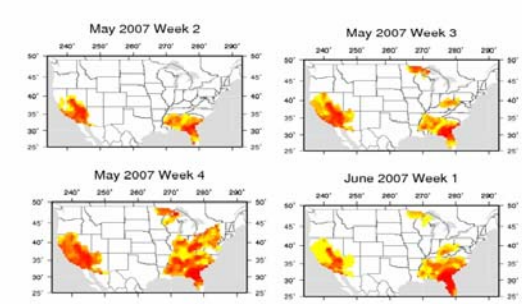



Figure 5: Estimated extent of drought over continental U.S. as of first week of June, 2007, and evolution over previous three weeks. Soil moisture percentiles are relative

week. We are interacting with CPC personnel who are reviewing the method, but we believe that it has great promise for producing a more objective delineation of drought extent and severity that is currently possible in publications such as the National Drought Monitor.

In streamlining our implementation of the ESP approach to streamflow forecasting, we explored the necessity of calibration when applying an ESP approach to seasonal forecasts. This work looks at bias reduction via model calibration versus "training" a bias removal technique on retrospective simulation error statistics and removing bias during post-processing. Forecast error, as measured by the coefficient of prediction, of these two methods was found to be similar for each case, and in many cases, the reduction is greater for post-processing bias correction, by percentile mapping, at the seasonal scale. This work has been accepted for publication (Shi et al., 2007).

Since soil moisture in land surface models is dependent on model dynamics, we have investigated the use of multi-model ensembles. Tests of model-specific sensitivities in identifying and reconstructing drought events, based on model-predicted soil moisture, were conducted using six land surface/hydrology models over the continental United States for the period 1920-2003. We also applied two ensemble methods to combine results from all of the models. Combining models is thought to minimize any model errors. All models and the two ensembles identified the spatial patterns of major drought events. The spatial distribution of drought severity and duration was plausible for all models; however, models differed in these aspects. Differences between models were greater in the western U.S. than in the eastern U.S. due to precipitation differences. Deeper soil columns led to longer soil moisture memory. The multimodel ensembles have been implemented into the real-time drought nowcast system of the U.W. Surface Water Monitor. This work has been submitted for publication.

After further investigation into techniques for incorporating groundwater into large-scale land surface models, we have incorporated the simple groundwater model (SIMGM) developed for the Community Land Model (CLM) by Niu et al. (2007) into VIC. This model is much more computationally efficient than the Liang et al. (2003) VIC-ground model, which we originally proposed implementing, and has been successfully run globally, with results that closely match water table levels derived from the Gravity Recovery and Climate Experiment. SIMGM includes a lumped-unconfined "aquifer" as a single integration element beneath the soil column. The hydraulic properties, including specific yield and exponentially decaying hydraulic conductivity, of this layer differ from those of the soil layers.

The basic concept behind SIMGM is a simple water balance, i.e. the change in water storage within an aquifer over time equals the difference between recharge into and subsurface flow out of the aquifer. Recharge is calculated using Darcy's law as a function of the depth to the water table and the matric potential and mid-element depth of the lowest unsaturated soil layer. The recharge estimate also accounts for an upward flux driven by capillary forces. The CLM implementation of SIMGM uses a simple TOPMODEL-based runoff model to calculate subsurface flow (baseflow) as an exponential function of water table depth. Unlike in TOPMODEL, Niu et al. (2007) estimate saturated hydraulic conductivity as a function of soil texture; in the aquifer, hydraulic conductivity exponentially decays with depth from that of the lowest soil layer. Water table depth is estimated from the resultant aquifer water storage scaled by the specific yield. Depth to the water table can be within the soil column, in which case the water table depth calculations differ slightly to account for differences in soil and aquifer properties. The water table can also be below the base of the lumped, unconfined aquifer element; hence, there is no prescribed total model depth.

The VIC implementation of SIMGM differs from that of Niu et al. (2007) primarily in the surface runoff scheme. Whereas CLM applies a TOPMODEL-based runoff scheme to parameterize surface runoff as a function of topographically based saturated fraction and water table depth, VIC calculates surface runoff using a more generalized parameterization. Also, the standard VIC model includes 3 soil layers, as opposed to the 10 layers of CLM. In order to maintain the simplicity of the VIC model, we have not altered the 3-layer construct. The thrust of work in this reporting period has been calibration and testing of the VIC model with and without SIMGM.

We have calibrated the VIC model with and without SIMGM over the Little Wabash River IL, the Bruneau River, ID, the Salmon River, the North Fork Flathead River, MT, and the Yellowstone River, MT. For all of these rivers, VIC reproduces daily streamflow equally well with or without SIMGM. The inclusion of SIMGM does impact the distribution of water in the annual average water budget (Figure 6). Summertime evapotranspiration is higher in SIMGM in the Little Wabash River, where the primary vegetation cover is forest. This leads to lower wintertime baseflow. In the Salmon and North Fork Flathead rivers, evapotranspiration is minimally effected; however the partitioning of streamflow between runoff and baseflow is greatly altered, with near-constant baseflow in the SIMGM implementation, which contrasts the seasonal cycle of baseflow in the standard VIC implementation. We have obtained Ameriflux measurements of latent heat in the Feather River basin and intend to test the performance of VIC with and without groundwater in simulating evapotranspiration.

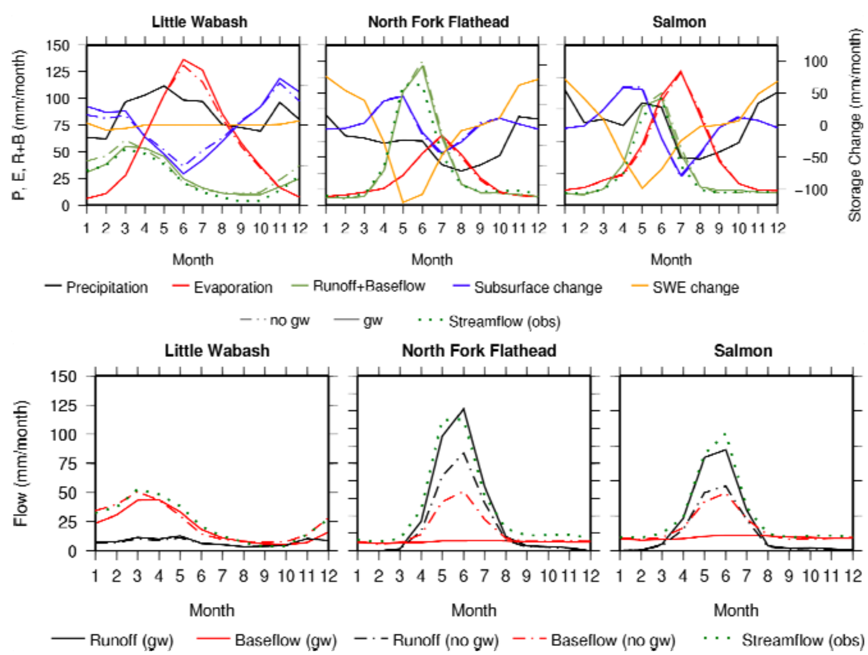



Figure 6. Top panel shows the modeled average annual water balance (1950-1998) for the Little Wabash, North Fork Flathead and Salmon Rivers. Lower panel shows the modeled average annual runoff and baseflow plotted against observed streamflow for the same rivers. Dashed lines are the standard VIC implementation; solid lines

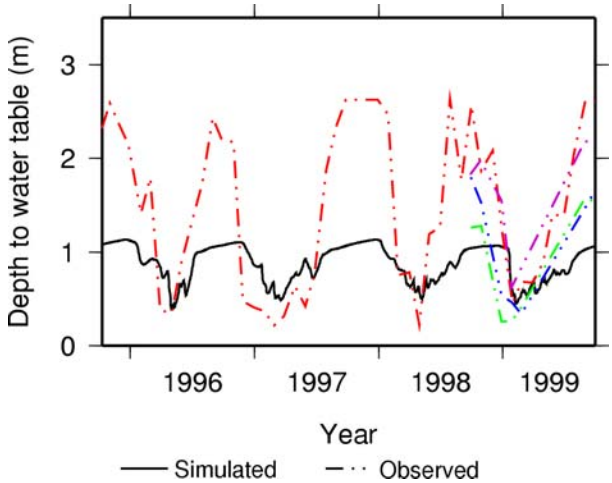



Figure 7. Depth to water table, simulated by VIC with SIMGM for the Little Wabash River (solid) and observed by the ISWS at Olney (blue), Fairfield (green), Dixon Springs (red) and Rend Lake

Simulated basin-average water table levels for the Little Wabash River track the timing of seasonal cycle of the observed well level data (from the ISWS climatological shallow groundwater WARM and ICN networks in Illinois) fairly well; however, individual wells tend to become much drier (higher depth to water table) during winter months than simulated water levels (Fig. 7). Water levels match somewhat better at Fairfield (green line in Fig. 7), which is the nearest station. The observations are somewhat incongruent with the model results due to the heterogeneity across scales. There are few groundwater level measurements in the western U.S. that are included in the U.S.G.S. Climate Response Network (CRN wells deemed unaffected by pumping). The CRN wells in Idaho and Montana measure very deep water levels (~100 ft), whereas VIC with SIMGM models water levels on the order of 3-6 ft deep. This suggests that SIMGM, which is designed to model shallow groundwater, is effectively acting as an additional soil layer in these regions of deep groundwater. This might also explain the baseflow response in these regions.

For droughts, we are particularly interested in whether the persistence of drought conditions will be impacted by the inclusion of groundwater in VIC. To investigate this, we examined the autocorrelation of streamflow and of subsurface storage in each model. Figure 8 shows the results for streamflow in the Little Wabash River. In this case, a slightly autocorrelation (over 1-, 3-, and 6-month lags) occurs when groundwater is modeled; however, this correlation is higher than observed. In the Salmon and North Fork Flathead rivers, on the other hand, the streamflow shows a smaller lagged correlation, which is also closer to the observed, when groundwater is modeled than in the original VIC version. Subsurface storage tends to be highly autocorrelated in both models, though the storage in the groundwater model shows a stronger relationship where the autocorrelation in streamflow is weaker. The

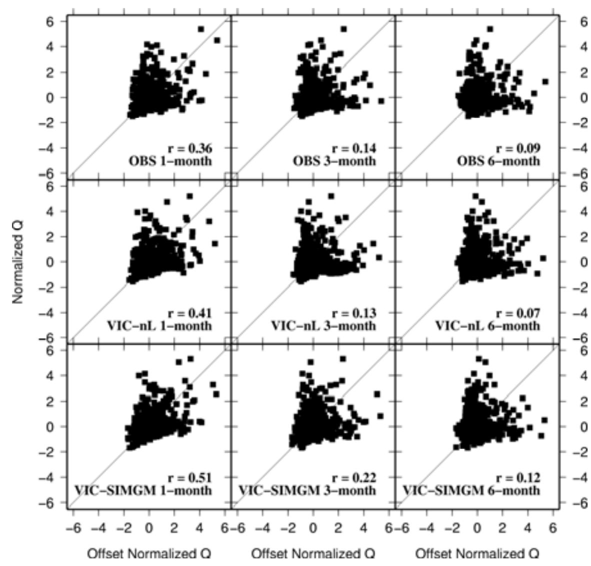



Figure 8. Autocorrelation of streamflow for the Little Wabash River in Illinois. 1-month lag time, 3-month lag time, and 6-month lag time shown from left to right. Top: observed, middle: VIC without SIMGM, bottom: VIC with SIMGM. Correlation coefficients labeled on plot.

similarities in these correlations; however, suggest that the standard VIC model reproduces the persistence of hydrologic conditions equally well as the VIC model with groundwater. A paper summarizing these results is in preparation.

Additional work is needed to incorporate groundwater level data into the VIC model through calibration or assimilation. Although SIMGM has a moveable lower boundary condition, it is designed for use in shallow aquifers. As such, regions with very deep water levels may need to be masked out in continental application of the VIC model with SIMGM.

This coming year of work will also involve activities to implement and use the model in drought decision-making. We have a unique opportunity to further develop the groundwater monitoring and forecast system in applications in California to support the NIDIS (National Integrated Drought Information System) initiative, and drought planning processes underway in the State of California. PI Steinemann will be working closely with the USGS collaborators on this project at the USGS California Water Science Center (in San Diego) and at the Scripps Institution of Oceanography (at U.C. San Diego), and with water managers in the use of the system. We have already identified candidate regions for applications in California (e.g., Central Valley, Pajaro Valley, San Diego County, State of California), and key decision-makers and stakeholders who have indicated their interest in using the system developed under this project.

# Adaptive Management of Mountain Forests to Prevent Mass Wasting under Climate Change

## Basic Information

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|---|---|
| **Title:** | Adaptive Management of Mountain Forests to Prevent Mass Wasting under Climate Change |
| **Project Number:** | 2009WA255B |
| **Start Date:** | 3/1/2009 |
| **End Date:** | 2/28/2010 |
| **Funding Source:** | 104B |
| **Congressional District:** | Washington 5th |
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| **Focus Category:** | Climatological Processes, Hydrology, Sediments |
| **Descriptors:** | None |
| **Principal Investigators:** | Jennifer Adam, Balasingam Muhunthan |

## Publications


1. Barik, M., and J.C. Adam, 2009, Assessment of the Impacts of Climate and Land Cover Change on Landslide Susceptibility, presented at the State of Washington Water Research Center (SWWRC) Conference, Skamania, Washington. Best poster presentation award.
2. Barik M., T. Lopes, J.C. Adam, M.E. Barber, and B. Muhunthan, 2009, Analysis of Long-term Landcover and Climate Change Effects on Slope Stability. Water and landuse in the Pacific Northwest: integrating communities and watersheds conference. Stevenson, Washington. Honorable mention award.
3. Barik, M., and J.C. Adam, 2009, Impacts of Land Use Management and Climate Change on Landslide Susceptibility over the Olympic Peninsula of Washington State, presented at the American Geophysical Union (AGU) Fall Conference, San Francisco, California.
4. Barik M., and J.C. Adam, 2010, Landslide Susceptibility Mapping to Inform Landuse Management Decisions in an Altered Climate. Hydrology in the 21st Century: Links to the Past, and a Vision For the Future Steve Burges Retirement Symposium. Seattle, Washington.
5. Barik, Muhammad G., 2010, Landslide Susceptibility Mapping to Inform Landuse Management Decisions in an Altered Climate, MS Dissertation, Department of Civil and Environmental Engineering, Pullman, Washington, 55 pgs.
6. Barik, M., J.C. Adam, M.E. Barber, B. Muhunthan, Assesment of the Impacts of Climate and Land-cover Change on Landslides Susceptibility (To be submitted to Water Resources Research).
7. Barik, M., J.C. Adam, M.E. Barber, B. Muhunthan, Landslide Susceptibility Mapping to Inform Landuse Management Decisions in an Altered Climate. (To be submitted to Engineering Geology).

## 1. Problem and Research Objectives:

The current Habitat Conservation Plan for the Olympic Experimental State Forest (OESF), managed by the Washington State Department of Natural Resources (DNR), requires research be carried out to improve the effectiveness of conservation strategies while moving from short- to long-term solutions. Included in these management strategies are several options designed to protect endangered wildlife and aquatic species through establishment of riparian buffers to prevent mass wasting. Due to the hilly topography and wet weather condition this region is vulnerable for landslides, thus many failures of hillslopes in the Olympic region have been influenced by rainfall infiltration and loss of suction. Existing strategies based on past slope behavior may not adequately factor in the effects of climate change nor the hydrologic impacts of land use changes due to regional timber harvesting is considered. Management decisions for forest nation-wide can be improved by a systematic approach for evaluating the effects of projected climate change on slope stability under various management conditions.

Our overarching goal is to evaluate long-term solutions for the management of riparian areas in landslide prone areas under the effects of predicted climate change. The objective of this project is to determine the feasibility of using coupled hydrology/slope stability models to update remote sensing-based LSIs for a range of climate and vegetation scenarios to inform forest management practices. To achieve our objective, we pose the following specific questions:

1. What blending of remote sensing products will produce LSI's that have a high degree of predictability of mass wasting events?
2. How will the LSI change in response to projected climate change and alternative forest management practices?
3. How will changes in LSI affect suspended sediment concentrations in streams?

## 2. Methodology:

### *LSI over the Olympic Peninsula*

Landslide occurrence depends on complex interactions among a large number of factors. Among static factors, previous studies (Dai and Lee 2002; Carrara et al. 1991; Anbalagan et al. 1992; Larsen and Torres Sanchez 1998; Lee and Min 2001; Saha et al. 2002; Fabbri et al. 2003; Sarkar and Kanungo 2004; Coe et al. 2004) demonstrated that six parameters; slope, type of soil (clay, loam, percentage of clay), elevation, land cover, soil texture and drainage density, are closely associated with landslide occurrences. We have followed Hong et al. (2007) to develop the conventional LSI. Remote sensing products were utilized for deriving these various parameters. Several geospatial data sets were used in this study with the resolution of 200m.

*Principle of construction*

The landslide susceptibility mapping method used in this study consists of the following steps:
1) Classifying landslide-controlling factors into nominal categories with a continuum of increasing susceptibility to shallow landslides;
2) Assigning susceptibility values from zero to one for each factors; and
3) Mapping the landslide susceptibility using weighted linear combination methods.

*Assignment of numerical values for landslide-controlling factors*

We assigned a numerical value between zero and one to each and every factor class. For the slope and elevation map units, zero susceptibility values were given to flat slope and the lowest elevation; whereas susceptibility value one is assigned to the class of steepest slopes and the highest elevation. The Digital

Elevation Model (DEM) source was the Shuttle Radar Topography Mission (SRTM 2000) 1 arc-second resolution elevation dataset (U.S. Geological Survey 2000). The land cover data which were derived from NOAA's Coastal Change Analysis Program (NOAA 1990) used year 2001 Landsat-TM imagery (NASA 1999). The whole Olympic Peninsula was classified into 17 types of landcover types. From Larsen and Torres Sanchez (1998) study, numerical numbers between zero to one were assigned to each landcover class depending on their susceptibility to landslides. For the assignment of susceptibility to soil texture, we looked at porosity values which range from 0.1 for bedrock to 0.8 for Alluvium.
Final landslide susceptibility values are combined results of the numerical values assigned to each of the landslide-controlling parameters. According to Sakar and Kanungo (2004) studies, high infiltration is causing more instability in the area. Considering that the higher the porosity is, the higher infiltration is, we applied the same technique as used for soil texture on groundwater.

*Weighted linear combination*
To represent and interactively examine landslide-controlling parameters, we used the GIS overlay concept of weighted linear combination (WLC). In this study, the weighted linear combination method is performed to derive the final susceptibility values, as shown in the following equation:

$$Z(i,j,t) = \sum_{k=1}^{n} w_k y_k(i,j,t), where \sum_{k=1}^{n} w_k = 1$$

Z(i, j, t) is final susceptibility value for pixel (i, j) and $w_k$ is the linear combination weight for $k^{th}$ factor, where k = 1–5 in this study. Indeed, the difference between soil texture and type of soil was not clear in Hong et al. 2007 and in every other paper listed on it. Thus, we decided to consider soil texture and type of soil as one and same parameter.

***Response of LSI to timber harvesting and climate change over the Queets Basin***
*Study Domain*
For this study the Queets Basin was selected because it has wide range of geographical properties (e.g. steep slopes and high elevation) with a long period of recorded historical streamflow data (1948-present) and an inventory of landslide.

*Hydrologic and Slope Stability Modeling*
For this study, we applied the Distributed Hydrology Soil Vegetation Model (DHSVM; version 3 r2) (Wigmosta et al. 1994), which is a fully-distributed physically-based hydrology model with a stochastic mass wasting component (Doten et al. 2006). Spatial distributed data required by this model are elevation, soil data vegetation. For the hydrologic portion we have used the resolution of 150 m. The Digital Elevation Model source was the Shuttle Radar Topography Mission (SRTM 2000) 1 arc-second resolution elevation dataset (U.S. Geological Survey 2000). We applied a 10 m DEM for the mass wasting part collected from the University of Washington Geomorphological Research Group (UWESS 2001). The soil classification was obtained by University of Washington researchers (under the Hood Cannel Project; HCDOP 2005), who reclassified Washington State DNR (WADNR 2003) soil survey data into 18 soil texture classes using the soil texture triangle developed by the U.S. Department of Agriculture (Soil Conservation Service 1975). The maximum soil depth was taken as 2 m, as shallow landslides that occur in the Pacific Northwest are limited to this depth (Schmidt et al. 2001; Doten et al. 2006). The land cover data were derived from NOAA's Coastal Change Analysis Program (NOAA 1990) which used year 2001 Landsat-TM imagery (NASA 1999).

The metrological data used in this study were developed by Deems and Hamlet (2010), who extended (1915-2006) and improved the Maurer et al. (2002) gridded data. For the validation of our results with the historical landslides, we applied the Washington State DNR digital landslide database (1900-2000), which was developed under the Landslide Hazard Zonation Project (DNR 2009). We applied Landsat 5-TM (NASA 1984) images to identify historical deforestation activities using the supervised classification method as applied by Sohn and Rebello (2002).

*Susceptibility Mapping*

For landslide susceptibility mapping, we used a bivariate statistical method which was first developed by Yin and Yan (1988), later simplified by Van Westen (1997), and applied by Saha et al. (2005).

*Climate Change Scenarios*

For regional or basin-scale climate change studies, downscaled climate data generated from Global Circulation Models (GCMs) are required. We selected CGCM_3.1t47 (Kim et al. 2002) and CNRM-CM3 (Salas-Mélia et al. 2006) as they have resulted in the least amount of precipitation bias when compared with observed climate data (Mote and Salathe 2010). We applied the Elsner et al. (2010) downscaled precipitation and temperature output from these GCMs. The IPCC GHG emissions scenarios A1B and B1 were selected, as they are high and low scenarios, respectively (Nakicenovic and Swart 2000).

*Harvesting scenarios*

Logging scenarios were selected based on different slope, elevation, soil, and vegetation classes. Clear-cutting was simulated by changing root cohesion, tree surcharge, and the tree rainfall interception fraction.

*Model Evaluation*

The DHSVM implementation over the Queets Basin was calibrated and evaluated with historical USGS streamflow measurements at the outlet of the Queets Basin. The streamflow record was divided into the calibration and evaluation periods of 1991-1995 and 1985-1990, respectively. The Nash Sutcliffe efficiency (Nash and Sutcliffe 1970) for streamflow was 0.74 and 0.71 over the calibration and evaluation periods, respectively; while the relative bias for annually-averaged streamflow was -13% and -8% for the calibration and evaluation periods, respectively. Figure 1 shows simulated streamflow for the calibration period of 1985-1990.

Three sub-basins from the Queets were selected for application of the mass wasting module. The largest storm events during 1985 and 1981 were selected to evaluate the mass wasting model over sub-basins 1 and 2, respectively. The relative biases between predicted and historical landslide area are 7.4% and -10.4% for sub-basins 1 and 2, respectively.

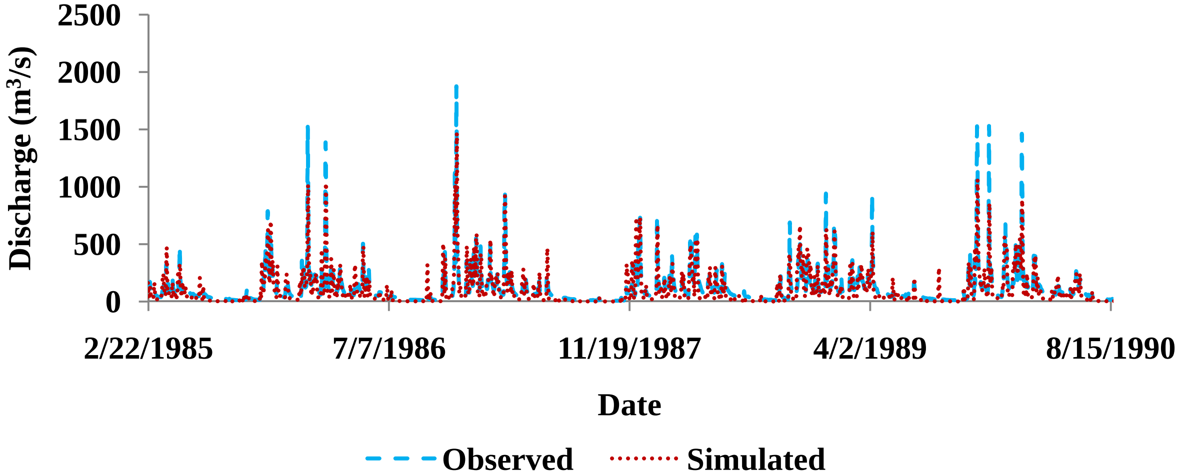


Figure 1. Observed and modeled streamflow over the evaluation period of 1985-1990, for which the Nash Sutcliffe efficiencies and relative biases are 0.71 and -13%, respectively.

*Weights for Each Landslide-Controlling Factor and Susceptibility Classes*

The landslide activity in the baseline scenario was subtracted from the landslide activity in each of the harvesting scenarios to isolate the failure events that were influenced by logging activities. The simulated failures in different harvesting classes were used to calculate the weights. To calculate these weights, we ran the DHSVM mass wasting module for the largest storm events occurring in each of the seven years between 1984 and 1990. To compare these weights against historical landslide activity, we selected an area near the mouth of the Queets Basin that has experienced logging-related landslides. The observed landslides between the period of 1990-1997 were identified using the DNR HZP inventory (DNR 2009). The Saha et al. (2005) probability distribution approach was used to determine the susceptibility classes; high, medium, and low. The susceptibility map was created for the harvested areas in that region by summing the appropriate weights. Our results showed that higher susceptibility classes are associated with higher landslides frequency values.

## 3. Principle Findings and Significance:

### *LSI over the Olympic Peninsula*

The LSI map developed by this method (Figure 2) gives us an overall idea about vulnerability of the area to the landslides. However, this conventional method does not consider the effect of land use change and there is no provision for incorporating the impact of future climate change. This is why we have developed another method incorporating these two global change issues.

### *Response of LSI to timber harvesting and climate change over the Queets Basin*

### *Effect of Timber Harvesting*

*Model Scenarios*

To investigate individual contributions of different factors, we have analyzed the post-harvesting sensitivity of landslide activity to different slope, soil and vegetation classes. The model showed that slope has strong controlling effect on landslide activity. The highest slope class has more than twice the logging-induced landslide activity than the lowest slope class. To explore the sensitivity of logging-induced landslide activity under varying soil textures and pre-logging forest types, we applied a theoretical basin approach to isolate the influence of each of these factors. This involved covering the entire sub-basin with uniform soil or vegetation conditions and examining the resulting increase in landslide activity due to clear-cutting for each of the soil and vegetation classes. Comparing among the soil types, we observe that silty clay loam followed by talus and silty loam are the most susceptible soil classes to landslides. We also did a sensitivity analysis for all of the forest classes with a constant soil type. The extraction of coastal coniferous forest results in the highest amount of loss in root cohesion among all of the forest types, resulting in high post-harvest landslide susceptibility.

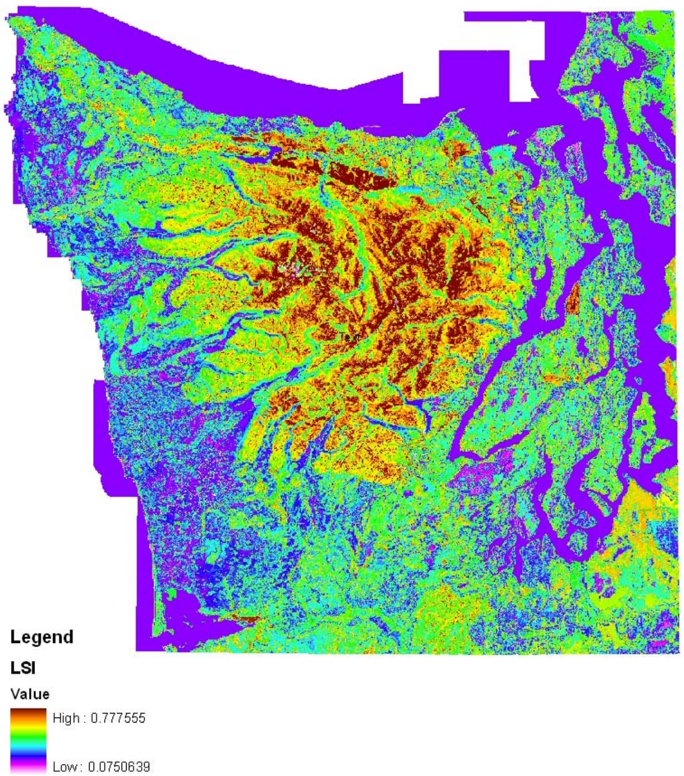


Figure 2**.** LSI map for the Olympic Peninsula region.

*Climate Change Effects on Logging-Induced Landslide Activity*

We repeated our model simulations for the pre and post-harvest scenarios using year 2045 downscaled GCM data for each of the A1B and B1 GHG emissions scenarios. Landslide susceptibility maps over the Queets Basin were created for each of the climate change scenarios. For all of the climate change scenarios, the same landslide susceptibility thresholds (0.05 and 0.79, based on landslide susceptibility classes for historical climate) were applied to create three susceptibility classes. The number of pixels within the low susceptible class remained nearly constant but the number of pixels in the high susceptible class increased from between 3.21% to 11.07%, depending on the scenario. The highest increment (11.1%) is seen for the CNRM-CM3 model under the A1B scenario. The areas within the medium susceptibility class decreased for each of the climate change scenarios due to the transfer of cells to the highest susceptibility class. Figure 3 shows the new areas that moved to the high landslide susceptibility class in response to projected climate change.

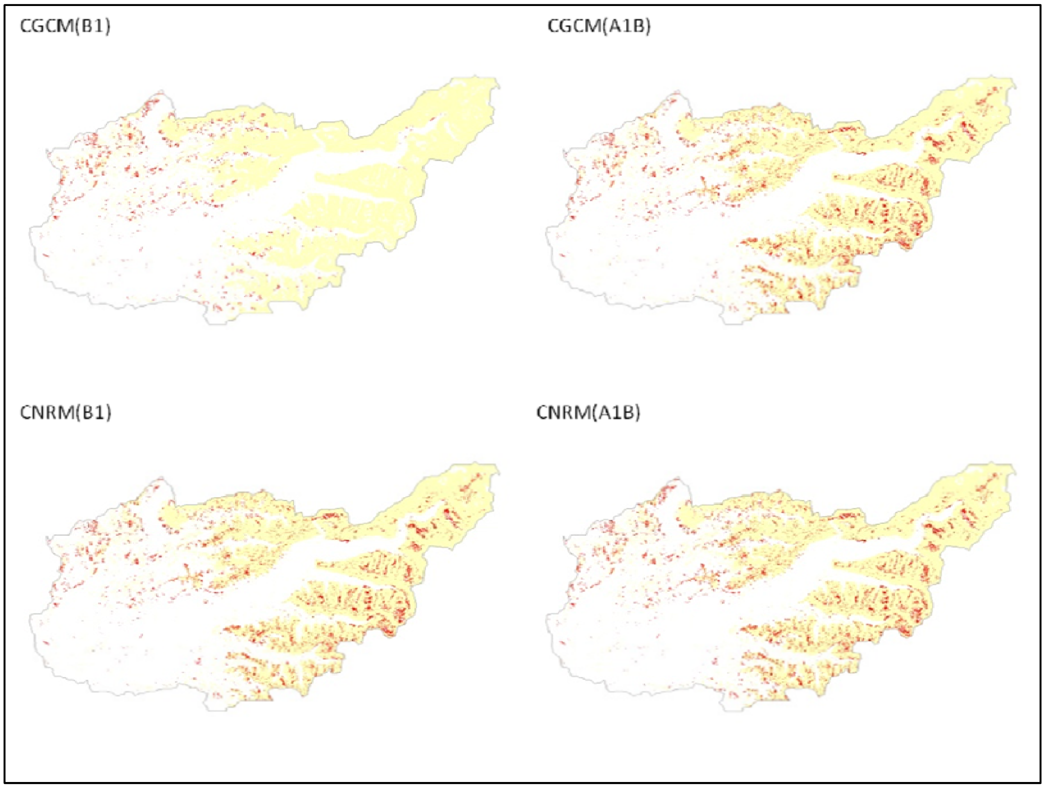

Figure 3. Increase in number of pixels in the high susceptibility class as a result of climate change for each climate change scenario (shown in red). The yellow pixels identify the high susceptibility areas for the historical climate scenario.

*Significance*
Using a distributed hydrologic model (DHSVM) with a mass wasting (landslide) algorithm, we have developed a method to map logging-induced landslide susceptibility for both historical and projected year 2045 climate scenarios, with the intent that this tool may be useful to forest managers in planning for climate change. Focusing on the Queets Basin on the western slope of the Olympic Peninsula, we show that climate change will increase logging-induced landslide susceptibility (for all GCMs and GHG scenarios considered). The extent of area within the highest landslide susceptibility class increased for all climate change scenarios. Thus, for long term forest management planning, these high-risk areas should be protected from logging. Landslide susceptibility increased on average 7.1% and 10.7% for B1 and A1B GHG emissions scenarios, respectively.

Results from our sensitivity simulations showed that logging-induced landslides are most sensitive in areas with steeper slopes, silty clay loam soils, and when logging in coniferous forests. For example, our baseline (pre-harvest) scenario for one of our sub-basins had a 0.008% failure area during a single storm event; but this failure increased to as much as 0.22%, 0.27%, and 0.18%, depending on slope, soil, and pre-harvest forest types, respectively. Considering how sensitive landslide response is to variations in soil, slope, and forest types; best forest management plans should be as site-specific as possible to minimize the ecological repercussions of logging-induced landslides while ensuring the economic viability of the timber industry.

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# Understanding Controls on Cyanobacteria Blooms: Vancouver Lake as a Model System

## Basic Information

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|---|---|
| **Title:** | Understanding Controls on Cyanobacteria Blooms: Vancouver Lake as a Model System |
| **Project Number:** | 2009WA264B |
| **Start Date:** | 3/1/2009 |
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| **Principal Investigators:** | Gretchen Rollwagen-Bollens, Stephen M. Bollens |

## Publications

1. Rollwagen-Bollens, G.C. and S.M. Bollens, Understanding Controls on Cyanobacteria Blooms: Vancouver Lake as a Model System, Freshwater Biology. (In preparation)
2. Rollwagen-Bollens, G.C. and S.M. Bollens, Managing Nutrient Input and/or Biological Controls for Vancouver Lake, Report will be submitted to Clark County WA Department of Public Works. (In preparation)

## Problem and Research Objectives

There is growing evidence that the incidence of noxious cyanobacterial blooms in freshwater lakes and rivers is increasing worldwide, most often associated with increased nutrient inputs, i.e. eutrophication (e.g. Dokulil & Teubner 2000, Sellner et al. 2003, Yamamoto & Nakahara 2005). Excessive abundance or "blooms" of cyanobacteria may have detrimental effects on lake ecosystems and water quality, including development of surface scums, depleted oxygen levels, and (in some cases) production of toxins that can negatively effect aquatic life and humans (Carmichael 1992, Sellner et al. 2003). This phenomenon is of great concern to water resource managers, particularly with respect to human health, as well as to the public whose use and enjoyment of these environments may be prohibited as a result.

Vancouver Lake, in Clark County, WA, is a large, shallow lake in the lower Columbia River floodplain that is popular with the local community for swimming, boating, fishing and other recreational activities (Figure 1). Vancouver Lake is also an important habitat for a range of fish species, as well as migrating and resident waterfowl, raptors and songbirds. Historically, Vancouver Lake was a relatively clear, moderately deep (6-8 m) lake flushed twice yearly by the spring and fall freshets of the Columbia River. Dam construction and diking along the south and west shoreline eliminated this natural flushing system, and urbanization in the surrounding drainage basin increased sedimentation rates, such that by 1981 the lake had shallowed to a depth of only 1 meter, on average (Gorini 1987).

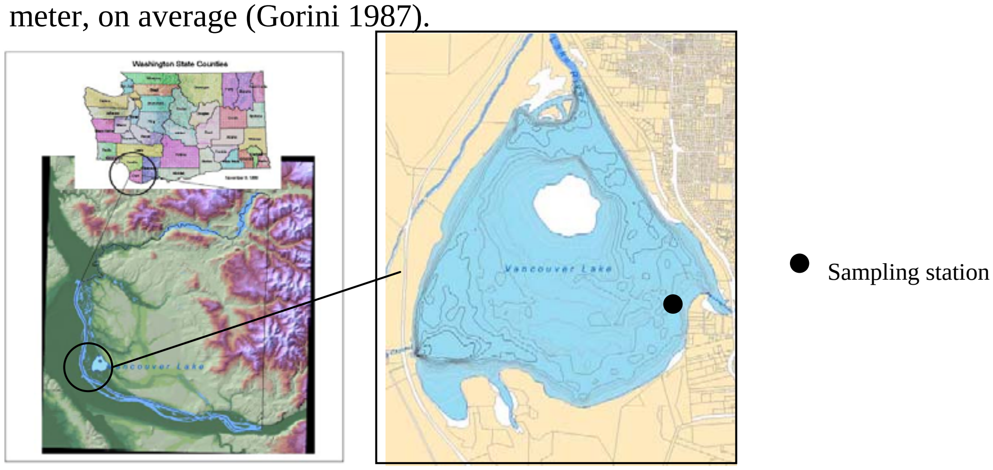


**Figure 1.** Bathymetric map of Vancouver Lake, located in Clark County, WA, in the lower Columbia River floodplain. Filled circle shows location of Vancouver Lake Sailing Club dock sampling station.

In response to this, an artificial flushing channel was constructed in 1983 as a means to re-establish flushing by the Columbia River and improve water quality. However, average depth remains ~1 meter and water quality in Vancouver Lake remains quite poor, with high levels of dissolved nitrogen and phosphorus, high turbidity, and high pH (Wierenga 2006, Rollwagen-Bollens & Bollens 2008). Most notably, Vancouver Lake has experienced numerous summertime blooms of *Anabaena* and *Aphanizomenon* cyanobacteria over the past 20 years, often necessitating closure of the Lake to swimming and other recreational use, however the blooms have been variable in intensity from year to year.

Increasing concern for the health of Vancouver Lake among local, state and federal agencies, private businesses, and citizens groups led to the formation in 2004 of the Vancouver Lake Watershed Partnership (VLWP). As part of its mission to better understand the processes that influence cyanobacteria blooms in Vancouver Lake, the VLWP recently partnered with the Aquatic Ecology Laboratory at Washington State University Vancouver (Bollens and

Rollwagen-Bollens, Principal Investigators) to undertake a biological assessment of the Lake. This assessment involved quantifying the distribution, abundance and composition of the planktonic organisms (i.e. algae, cyanobacteria, and both protozoan and crustacean zooplankton) in Vancouver Lake, as well as collecting a wide range of water quality data from locations throughout the Lake over an annual cycle (Bollens and Rollwagen-Bollens 2008). In summer 2008, the assessment project also included a limited number of experiments to measure the grazing rates of zooplankton consumers, in conjunction with measurements of cyanobacterial and algal growth rates.

In this project, we expanded on this biological assessment by measuring the dynamics and rate processes mediating trophic interactions among plankton populations in the Lake, in particular the balance of cyanobacterial and algal growth rates with the grazing rates of zooplankton consumers over the course of the 2009 bloom cycle. This allowed us to assess the role of grazing over a second year and thus describe the role of plankton grazers on a seasonal as well as inter-annual basis.

We had three major goals for this research. First, to quantify the balance of algal/cyanobacterial growth rates and zooplankton grazing rates over the cyanobacteria bloom cycle, and the relationship of this rate balance to biological (e.g. predator and prey community composition) and environmental factors (e.g. temperature, nutrient levels). Second, to provide a meaningful research opportunity for a WSUV master's student in Environmental Science. And third, to generate sufficient preliminary data and publications to develop a major, multi-year grant proposal to a federal funding agency such as NSF or EPA.

From February 2009 to February 2010 we completed the following tasks:.

*Task 1:* Conducted dilution experiments with Vancouver Lake protozoa, algae and cyanobacteria populations during 2009, and from these results estimated algal and cyanobacterial growth rates, as well as protozoan grazing rates.

*Task 2:* Conducted incubation experiments with Vancouver Lake metazoan zooplankton (copepods) feeding on natural assemblages of protozoa, algae and cyanobacteria, and from these results calculated zooplankton ingestion rates on these prey.

*Task 2:* Correlated observed growth and grazing rates with biological and environmental parameters.

*Task 3:* Applied the observed growth and grazing rates to the plankton abundance and composition data obtained during this and previous studies to estimate grazing impact over two full bloom cycles.

## Methodology

All sampling for this project was conducted from the dock at the Vancouver Lake Sailing Club, located on the southeast shore of Vancouver Lake (Fig. 1). All experimental protocols and microscopy were conducted in the Aquatic Ecology Laboratory at Washington State University Vancouver.

**Approach 1. Dilution experiments to assess algal/cyanobacterial growth and protozoan grazing rates.** We conducted 16 dilution experiments from February to December 2009. Lakewater containing the planktonic assemblage was collected from the surface using a clean, acid-washed bucket. Lakewater for particle-free dilutions was collected similarly, and then filtered through glass fiber filters into clean carboys. Each dilution experiment (Landry & Hassett 1982) was set up with five replicated dilution levels (10, 25, 50, 75 and 100%) of natural lakewater with filtered lakewater, including bottles for initial controls. All bottles were amended with added nutrients ($NO_3$ and $PO_4$). Bottles were incubated for 24 hours under ambient light conditions (light:dark) on a rotating plankton wheel inside a temperature-controlled chamber. Dilution bottles were sampled for chlorophyll biomass, and algal and cyanobacterial abundance at the beginning and end of each incubation.

**Approach 2. Incubation experiments to assess zooplankton prey preference and ingestion rates.** Separate experiments with adults of representative zooplankton taxa (copepods) feeding upon the natural assemblage of planktonic prey from Vancouver Lake were conducted concurrently with 4 dilution experiments between June and October 2009. Protocols followed Rollwagen-Bollens & Penry (2003) and Gifford et al. (2007). Zooplankton were collected via vertical hauls of a 73-µm plankton net, returned to the laboratory and adults of target species sorted under dim light into holding beakers. 500-ml incubation bottles were carefully filled with lakewater containing the natural assemblage of planktonic prey obtained from the surface using a clean, acid-washed bucket. Triplicate bottles containing only the natural assemblage were established as initial controls. Final controls (natural assemblage only) and final treatments (assemblage plus zooplankton predators) were prepared in triplicate and incubated in a temperature-controlled chamber for 24 hours on a slowly rotating (0.5-1 rpm) plankton wheel. All bottles were subsampled and analyzed to enumerate and identify the algae and cyanobacteria as described above (Approach 1). Zooplankton clearance rates (i.e. prey selectivity) and ingestion rates for each category of prey were estimated according to Marin et al. (1986).

**Approach 3: Comparison of growth and grazing rates in an environmental context.** The balance of algal/cyanobacterial growth rates with protozoan/zooplankton grazing rates are currently being evaluated in the context of environmental variables. To provide the environmental data, at each experimental sampling period a range of water quality parameters were measured from the surface to just above the bottom using a YSI 85 data logger, with probes for temperature, conductivity, and dissolved oxygen concentration. In addition, Secchi depths were recorded as an indicator of water clarity. Surface water samples were also obtained for measurement of nutrient concentrations ($NO_3$, $NO_2$, $PO_4$, $NH_4$, $SiO_4$), and sent to the Marine Chemistry Lab at the University of Washington for analysis.

## Principal Findings and Significance

The support from the Water Research Center allowed us to conduct experiments to determine algal/cyanobacterial growth and zooplankton grazing rates over a full bloom cycle in 2009. In conjunction with the experimental work, from March 2009 to February 2010 we also collected monthly (weekly during summer) samples from Vancouver Lake to monitor water quality and the overall plankton community to provide context for the rate processes. (Note: the grant from Water Research Center did not directly support the collection of these data, but are provided here for context.)

### I. 2009 Trends in Water Quality and Plankton Abundance/Composition

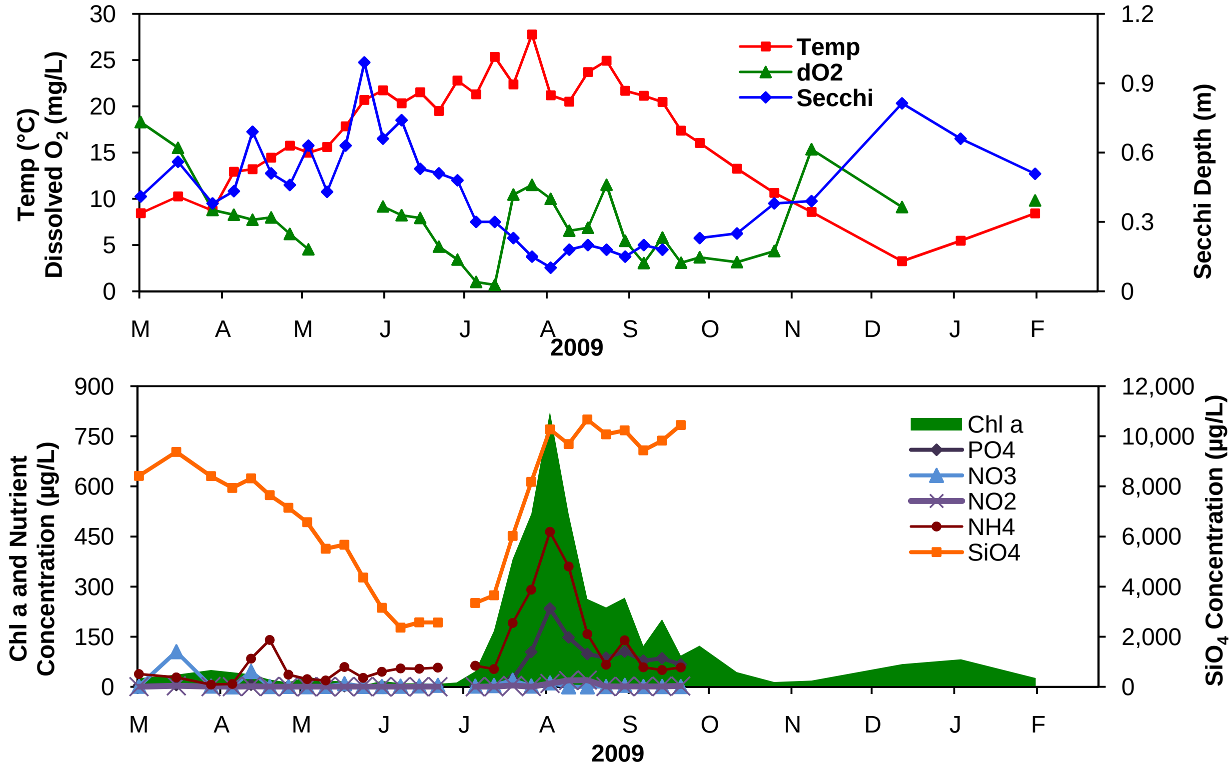


**Figure 1. Panel a: Surface temperature, dissolved oxygen concentration, and Secchi depth measured from the Vancouver Lake Sailing Club dock between March 2009 and February 2010. Panel b: Mean surface chlorophyll *a* concentration and mean surface concentrations of dissolved inorganic phosphate ($PO_4$), nitrate ($NO_3$), nitrite ($NO_2$), ammonium ($NH_4$), and silicate ($SiO_4$) collected from the Vancouver Lake Sailing Club dock between March 2009 and February 2010.**

***Water quality.*** Surface temperatures in Vancouver Lake ranged from 4-26°C between March 2009 and February 2010, with highest values from July to September, following the typical pattern for a temperate aquatic system. Dissolved oxygen concentrations were highest in winter/spring, but decreased markedly in June/July prior to the cyanobacteria bloom in late July 2009. Secchi depth, an indirect measure of overall water clarity, was deepest (i.e. relatively high water clarity) during spring 2009, but steadily shallowed through the summer, reaching <0.3 m in August and September 2009 (Figure 1a).

A seasonal signal was also readily apparent in the pattern of chlorophyll *a* concentration over 2009, with relatively low levels (~20-50 µg/L) throughout the year punctuated by an extremely large bloom from late July through early October 2009 (Figure 1b). Similarly, several important nutrients also peaked during this chlorophyll bloom period, including silicate ($SiO_4$), ammonium ($NH_4$), and orthophosphate ($PO_4$). Notably, nitrate nitrogen ($NO_3$) was low to undetectable throughout the spring and summer (Figure 1b).

***Cyanobacteria and protist plankton abundance and composition.*** Two distinct peaks in the abundance of cyanobacteria were evident during summer 2009. Cyanobacteria abundance reached ~$1.6 * 10^6$ cells/mL in early August, coincident with the peak of the chlorophyll bloom. Cyanobacteria reached a second, higher maximum in September, with abundances > $2.0 * 10^6$ cells/mL. This larger peak occurred after the chlorophyll bloom, and cyanobacteria abundance remained generally elevated through October (Figure 2).

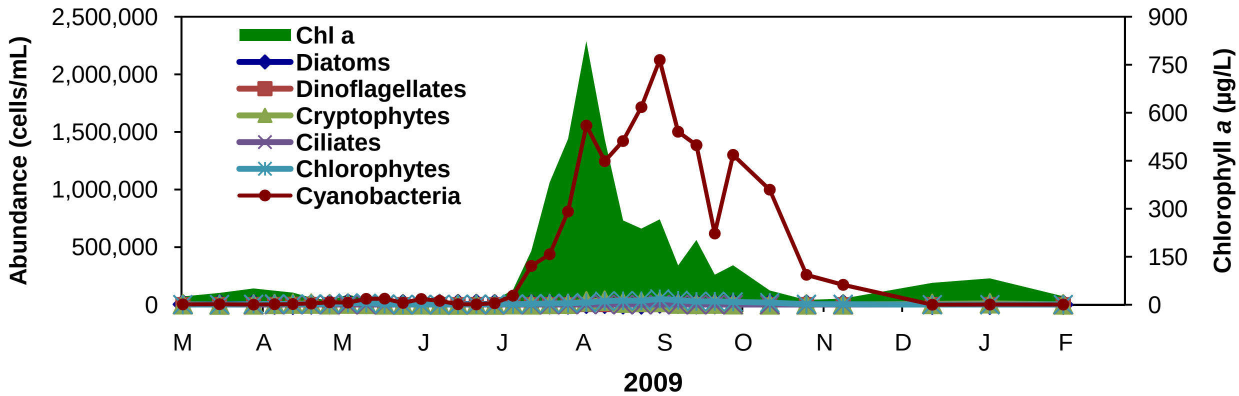


**Figure 2. Mean abundance of major taxonomic groups of protist plankton and cyanobacteria collected from the Vancouver Lake Sailing Club dock between March 2009 and February 2010. Green shaded area represents mean surface chlorophyll *a* concentration measured over the same period.**

Other important autotrophic protists (i.e. "algae") also showed seasonal peaks in abundance. Diatoms and flagellated algae (green algae or "chlorophytes" and cryptophytes) were abundant during spring 2008, but decreased during June and early July, a period of somewhat low nutrient concentrations. However, chlorophytes (especially *Scenedesmus*) and cryptophytes (particularly *Cryptomonas*) both showed very large peaks ($3.5\text{-}4.5 * 10^4$ cells/mL) near the end and following the chlorophyll bloom in August. Cryptophyte abundance remained elevated following a similar pattern as cyanobacteria (Figure 3).

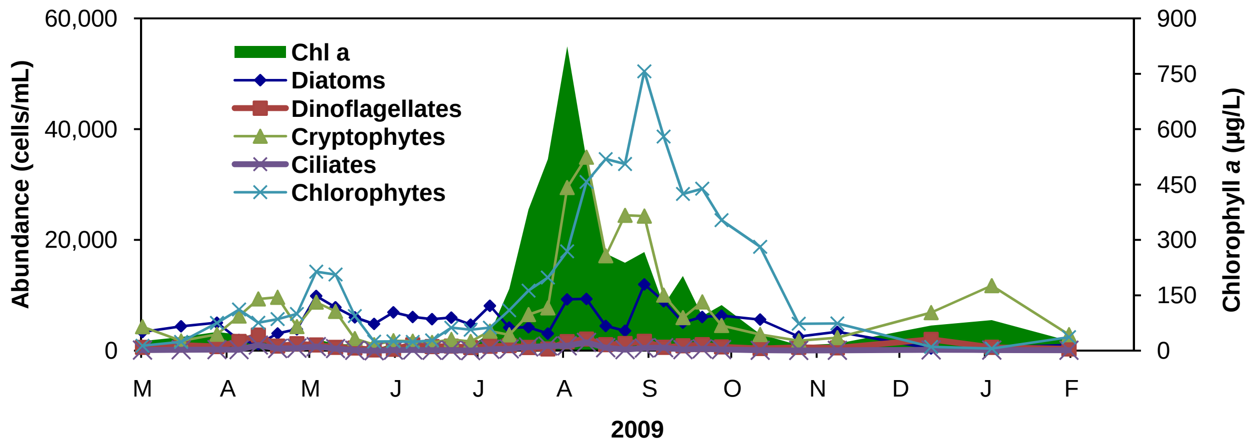


**Figure 3. Mean abundance of major taxonomic groups of protist plankton (without cyanobacteria) collected from Vancouver Lake Sailing Club dock between March 2009 and February 2010.**

The two major peaks in cyanobacterial abundance and biomass were distinctly different in composition. The early August 2009 peak consisted of a mixed assemblage dominated by *Anabaena flos-aquae* and a small number of less common taxa. In contrast, the second more prolonged peak in late August through October was strongly dominated by *Aphanizomenon flos-aquae* (Figure 4). Despite very high cyanobacteria abundance in September and October, chlorophyll a levels were much reduced from the peak early August. It is possible that *Aphanizomenon* abundance could have been somewhat overestimated during early fall, as this species forms densely aggregated, filamentous colonies that make enumerating individual cells problematic. In addition, the cyanobacteria cells may also have been low in chlorophyll content, indicative of the waning bloom.

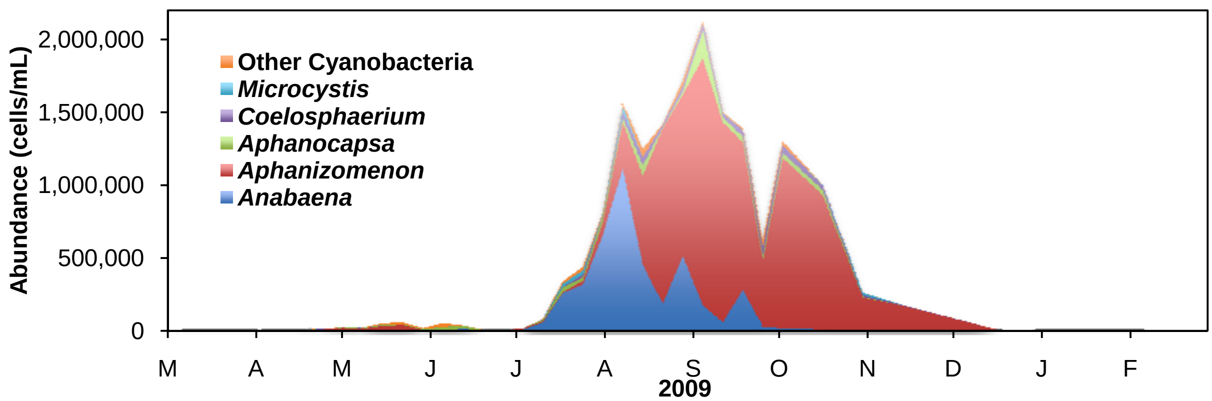


**Figure 4. Mean abundance of the major cyanobacteria taxa collected from Vancouver Lake Sailing Club dock between March 2009 and February 2010.**

There is clearly a compositional shift in the unicellular plankton community between winter, spring and summer in Vancouver Lake. A diverse assemblage of diatoms and flagellates in spring shifted abruptly in mid-summer to domination by cyanobacteria throughout the late summer and early autumn. Diversity increased again in winter, but to a community more dominated by cryptophytes and dinoflagellates (Figure 5).

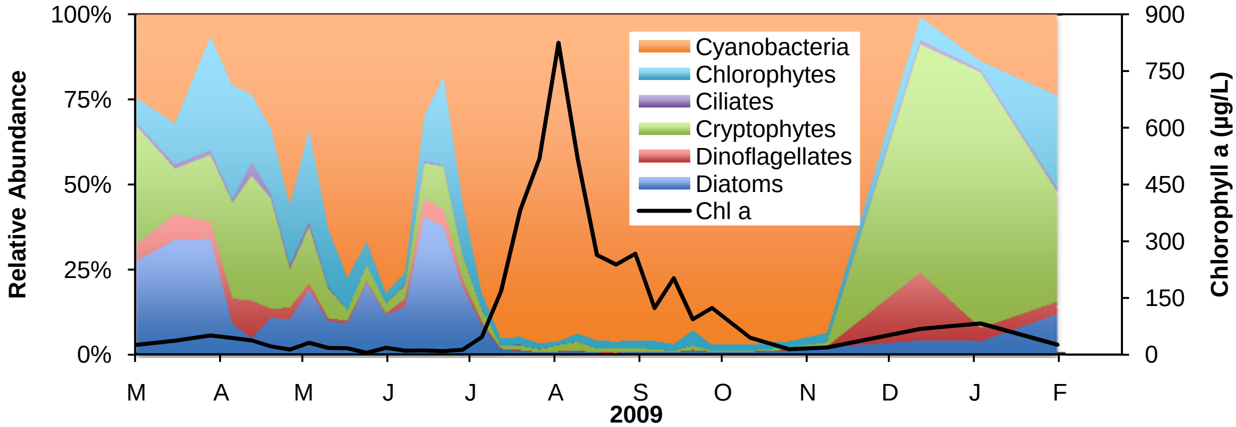


**Figure 5. Relative abundance of major taxonomic groups of protist plankton and cyanobacteria collected from Vancouver Lake Sailing Club dock between March 2009 and February 2010.**

***Metazoan zooplankton abundance and composition.*** Zooplankton abundance was highly variable throughout the year, dominated numerically by small rotifers (mainly *Polyarthra*, *Asplanchna*, *Brachionus* and *Keratella*), which exhibited a "boom-bust" pattern of high vs. low abundance. The major life stages of the copepod *Diacyclops thomasi* (naupliar larvae, juvenile copepodids and adults) also showed varying peaks, often with bursts of nauplii followed by peaks in juveniles and then adults. This cohort progression was particularly evident during and following the chlorophyll bloom in late August. Also notable was the shift from a cladoceran-dominated system in late spring, to a rotifer-dominated system in July just prior to the cyanobacteria bloom, to a copepod-dominated system during the bloom, back to a cladoceran-dominated system in late fall 2009 (Figures 6 and 7).

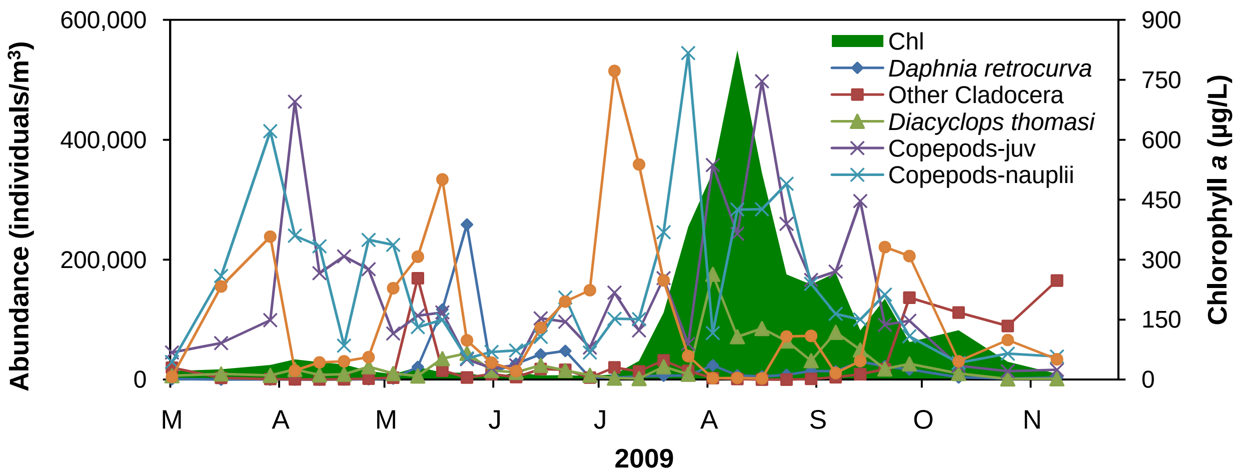


**Figure 6. Mean abundance of major taxonomic groups of metazoan zooplankton collected from Vancouver Lake Sailing Club dock between March 2009 and February 2010.**

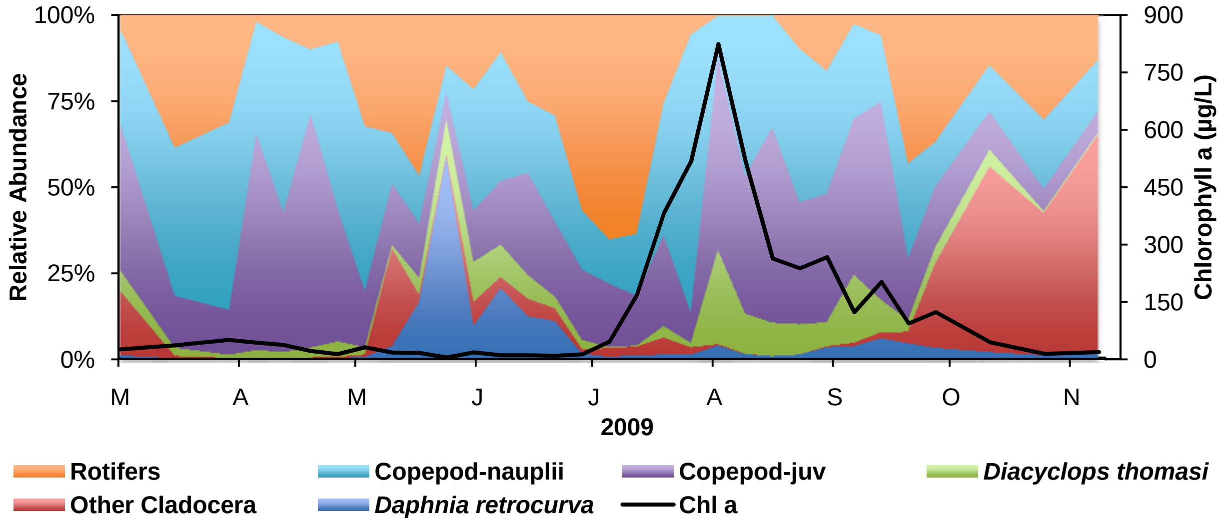


**Figure 7. Relative abundance of major taxonomic groups of metazoan zooplankton collected from Vancouver Lake Sailing Club dock between March 2009 and February 2010.**

## II. Algal Growth Rates and Zooplankton Grazing Rates

***Cyanobacterial/algal growth rates and protozoan grazing rates.*** Between February and December 2009, 14 dilution experiments were used to determine algal community growth rates and protozoan community grazing rates (Figure 8). Three additional experiments (conducted in March, April, May 2009) did not produce significant results and are not discussed. Each individual graph in Figure 8 shows how net growth of photosynthetic organisms (both cyanobacteria and eukaryotic algae), as measured by increases in chlorophyll concentration over each 24-hr experimental incubation, varied over different proportions of unfiltered lakewater diluted with filtered lakewater. The lines on each graph represent the linear regression between observed net growth rates of algae vs. the fraction of unfiltered lakewater in each incubation treatment. The y-intercept (as calculated in the regression model) is the estimate of "intrinsic" algal population growth rate (i.e. what algal growth would be without the presence of grazers). The slope of the regression line represents the community grazing rate of protozoan grazers. In general, the regression relationships were well-supported (mean $r^2$ values for all experiments > 0.5).

The relationship of algal community intrinsic growth rates (units: $d^{-1}$) to protozoan community grazing rates (units: $d^{-1}$) from each experiment over the course of 2009 are shown in Figure 9. In February algal growth and protozoan grazing rates were relatively low but nearly equal, suggesting the rate of protozoan grazing was high enough to keep pace with the rate of algal growth. However, from June to late July, prior to the chlorophyll a bloom, the relationship between algal growth rates and protozoan grazing rates diverged sharply, with algal growth of ~0.8 $d^{-1}$. [For perspective, a community growth rate of 0.7 $d^{-1}$ corresponds to a doubling of the population per day and a rate of 1.1 $d^{-1}$ corresponds to a tripling of the population per day, assuming exponential growth.] In June and July, the algal community (including cyanobacteria and eukaryotic algae) was therefore growing somewhat faster than a doublin per day.

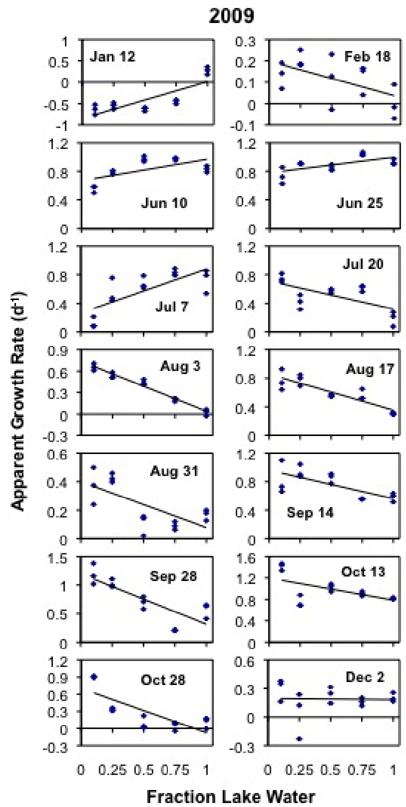


**Figure 8. Plots of regression relationships between net growth rates observed in treatment bottles and degree of dilution among treatments for 14 dilution experiments conducted using water and organisms collected from the Vancouver Lake Sailing Club dock between January and December 2009.**

Notably chlorophyll levels in the Lake were low during this period. Thus even though the algal community was doubling in size on a daily basis, the initial population sizes were small enough that overall algal biomass (as measured by chlorophyll concentration) did not evidence a "bloom." Another consideration is the effect of larger (mesozooplankton) grazers on algal biomass, as discussed below.

Algal growth rates during the cyanobacteria bloom period from late July through October were also high (>0.7 $d^{-1}$), and reached a peak of ~1.2 $d^{-1}$, equivalent to more than a tripling per day (Figure 9). However, protozoan grazing rates increased dramatically over the bloom period in step with the increasing algal growth rates, suggesting the protozoan grazer community maintained a substantial influence on algal mortality (Figure 9).

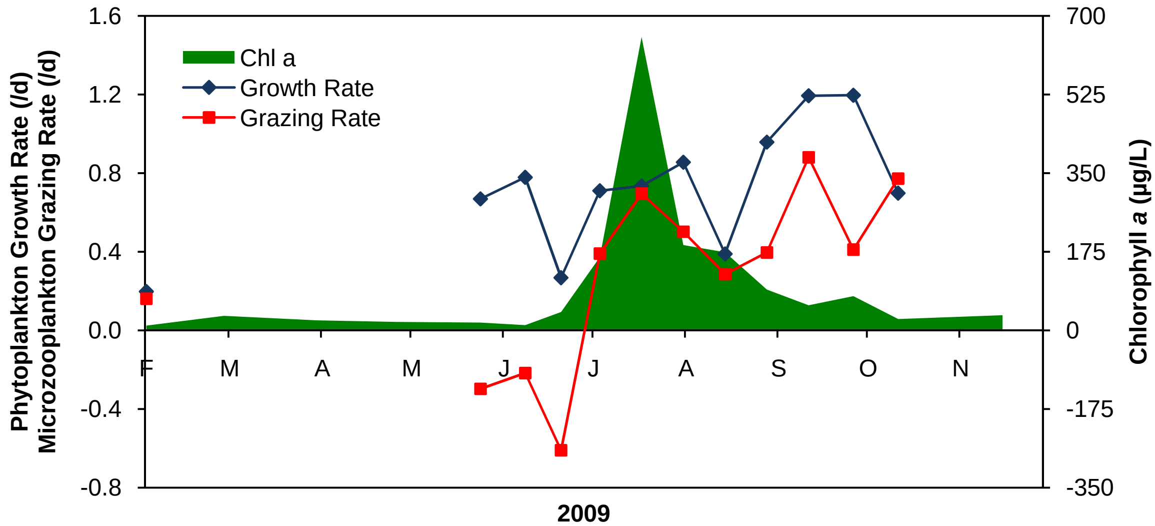


**Figure 9. Algal community intrinsic growth rates ($day^{-1}$) and protozoan community grazing rates ($day^{-1}$) estimated from dilution experiments conducted in Vancouver Lake between February and December 2009. Shaded area represents chlorophyll concentrations measured at each experimental sampling date.**

The most notable pattern in growth and grazing rates occurred during the 5-week period from mid-June to late July preceding the explosive increase in cyanobacteria abundance and chlorophyll levels. Protozoan community grazing rates were calculated to be negative during three experiments during this period. Negative grazing rates calculated from dilution experiments are the result of algal cells actually growing more rapidly in the presence of grazers.

The negative grazing rates observed in Vancouver Lake during June suggest there could have been a "trophic cascading effect" occurring during the incubations. In the bottles with full strength lakewater, there was likely a more complex community of protozoan grazers than in other experiments, in which a small number of large grazers (e.g. large ciliates) could have been consuming more abundant smaller grazers (e.g. small dinoflagellates) who then were prevented from grazing small algae. As a result, in undiluted treatment bottles small algae could increase in abundance over the incubation leading to high net growth rates. The dilution process selectively removes the least abundant organisms, therefore in the highly diluted treatments, the removal of large grazers would reduce grazing pressure on the smaller protozoan grazers, which would in turn allow the smaller grazers to exert higher grazing pressure on small algae. Thus very low net algal growth rates would be observed in the most diluted treatments, leading to a postive regression slope (and thus a "negative" grazing rate). We are pursuing this possibility by doing additional, more detailed, taxon-specific analyses of these samples.

***Zooplankton grazing rates.*** Feeding incubation experiments with metazoan zooplankton predators collected from Vancouver Lake were conducted in conjunction with protist community dilution experiments from June through October 2009. The zooplankton taxa selected for use as predators in each experiment were determined by observing the zooplankton community present at the time of sampling and choosing the one, and sometimes two, species that were both highly abundant and had enough individuals at or near the adult stage to ensure sufficient densities for all treatment bottles. The predator in each of the incubation experiments reported here was the copepod *Diacyclops thomasi*. In each experiment, 40 adult female copepods were incubated for

12 hours in a medium of unfiltered lakewater, and the change in prey abundances over the incubation used to calculate copepod ingestion rates and prey selectivity.

Figure 10 shows the prey preferences of *Diacyclops thomasi*, determined by comparing the relative abundance of prey taxa available at the beginning of the experiment to the relative abundance of prey taxa consumed during the incubation. In late June, prior to the chlorophyll bloom, >50% of the total prey field available to *D. thomasi* consisted of cyanobacteria cells (a mixed assemblage dominated mostly by *Aphanizomenon flos-aquae*) with diatoms and chlorophytes making up most of the remainder (25% and 15% respectively). By contrast, cyanobacteria represented 60%, chlorophytes 25%, and small flagellates 8% of the total cells consumed by *D. thomasi*, suggesting copepods were preferentially targeting these prey (Figure 10). In August, at the height of the chlorophyll bloom, cyanobacteria (mostly *Aphanizomenon*, but also *Anabaena flos-aquae*) accounted for nearly 95% of the total cells available to *D. thomasi*. Cyanobacteria also comprised ~95% of the diet of D. thomasi, indicating that the copepods were consuming their prey mostly in proportion to its availability (Figure 10). Finally, in October when *Aphanizomenon* cyanobacteria were near the end of their extended bloom, but chlorophyll levels had decreased, *D. thomasi* were apparently avoiding the consumption of cyanobacteria altogether, and instead consuming both small (<15 µm) and large (>15 µm) ciliates well out of proportion to their availability in the field (Figure 10).

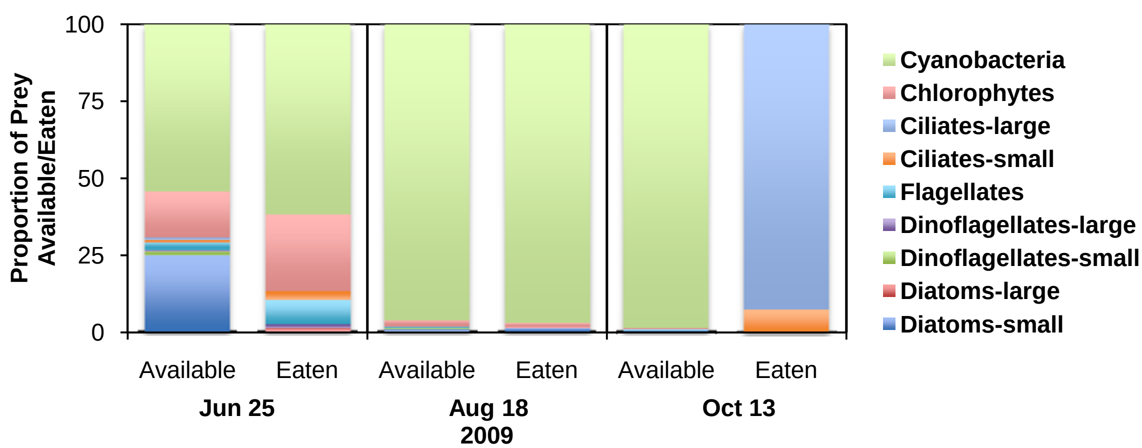


**Figure 10. Proportions of major prey taxa groups available to metazoan zooplankton (*Diacyclops* sp. copepods) compared to the proportions of major prey taxa groups consumed by the grazers during three 12-hour feeding incubation experiments conducted using organisms collected in Vancouver Lake over the summer/fall bloom period of 2009.**

The measured ingestion rates of *Diacyclops thomasi* adults reflect both the apparent prey preferences of the copepod as well as the magnitude of the abundances of different prey types. In June the rates of ingestion of prey carbon biomass (µg carbon consumed per predator per hour) were moderate, with the highest rates observed on large (>15 µm) dinoflagellates and ciliates (Figure 11). In August, copepod ingestion rates of prey carbon were substantially higher, with an exceptionally high ingestion rate on cyanobacteria (2.0 µg C/copepod/hour), a time when these cells were very abundant and of potentially higher nutritional quality, based on high chlorophyll concentrations, as compared to October. However in October, while cyanobacteria abundance was still high but chlorophyll levels were lower, *D. thomasi* ingestion rates were quite low and generally comparable on all prey types except cyanobacteria (Figure 11).

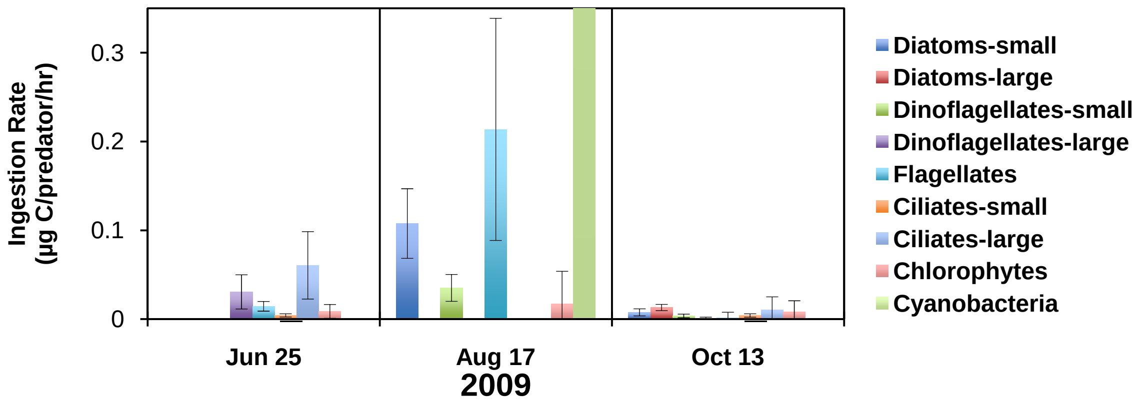


**Figure 11. Mean carbon biomass ingestion rates of *Diacyclops thomasi* adult female copepods feeding on natural assemblages of planktonic prey in Vancouver Lake during three incubation experiments conducted using organisms collected from the Sailing Club dock. Error bars represent 1 standard error. Value for ingestion rate on cyanobacteria on Aug 17 = 2.0 µg C/predator/hr.**

## III. Grazing Impact

***Protozoan grazing impact.*** The dilution experiment results produced quantitative estimates of algal community growth rates and protozoan community grazing rates, on a per day basis. These rates are particularly useful for assessing the pathways and fluxes of materials (i.e. carbon) through the planktonic food web. However, it is also useful to estimate the potential grazing impact of protozoan grazers on algal communities. The ratio of protozoan community grazing rates to algal/cyanobacterial community growth rates at in any single experiment is equivalent to the proportion of algal production per day. By applying these ratios to the concentration of chlorophyll a at the time of each experiment, it is possible to estimate the impact of protozoan grazing on the overall standing stock of the algal/cyanobacteria community. These grazing impact results are presented in Figure 12.

Protozoan grazing impact was low during February 2009, with protozoan grazing removing ~15% of algal standing stock per day. Interestingly, protozoan grazing impacts were negative during June and early July, during a period of low nutrient concentrations and negative protozoan grazing rates. As discussed above, this suggests potential trophic interactions among different types of protozoan grazers and algal populations, which may have resulted in the shift in algal community composition from dominance by diatoms to dominance by cyanobacteria. During the chlorophyll *a* peak from August through September, however, protozoan grazing impacts were relatively high high, ranging from 40-70% consumption of algal standing stock per day, and then increased further to around 100% of algal standing stock during early October (Figure 12).

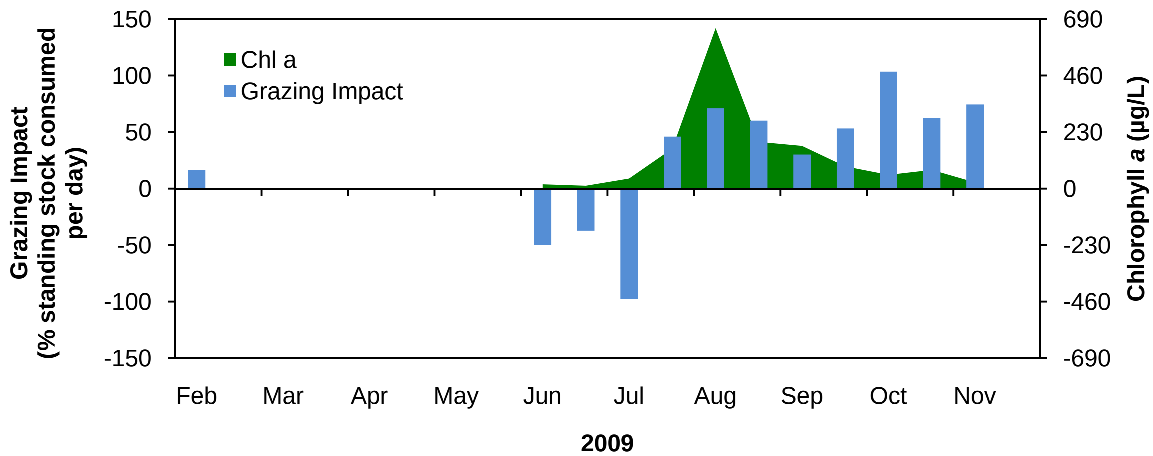


**Figure 12. Protozoan grazing impact, measured as the % of algal/cyanobacterial standing stock consumed per day, determined from dilution experiments conducted in Vancouver Lake between February and November 2009. Green area represents chlorophyll *a* concentration over the same period.**

***Metazoan zooplankton grazing impact.*** As with the protozoan grazers, it is useful to estimate the potential grazing impact of the metazoan zooplankton on algae/cyanobacteria in Vancouver Lake. For these grazers, their impact on the algal community was determined by applying the empirically derived individual predator ingestion rates to the densities of these predators measured in the Lake, and further comparing these copepod community ingestion rates to the abundance of algae present. Thus, grazing impact is here measured as the % of the algal community that was consumed by metazoan zooplankton per day, shown in Figure 13. Note that our experiments determined the ingestion rates of only a subset of the metazoan zooplankton predators present at any one time, namely the copepod *Diacyclops thomasi*. Thus these estimates of metazoan grazing impact are likely underestimates of the total grazing impact by all zooplankton predators.

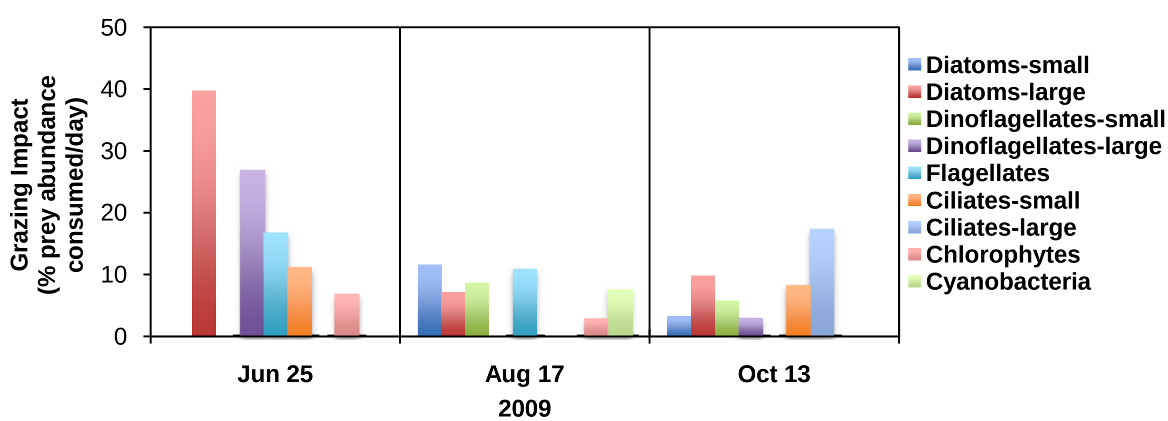


**Figure 13. Copepod grazing impact, measured as % of prey population consumed per day, of *Diacyclops thomasi* adults on planktonic prey from Vancouver Lake on three sampling dates over the 2009 bloom period.**

In June, prior to the bloom, copepod grazing impact on different categories of prey taxa was highest, ranging from 5-40% of the standing stock of these groups per day. The highest copepod grazing impact during June was on large (>15 µm) diatoms and dinoflagellates (Figure

13). In August, at the height of the bloom, copepod grazing impacts were lower, averaging ~8% consumption of a wide range of prey taxa per day, including cyanobacteria. In October, copepod grazing impact was comparable to August, however the grazing impact of copepods on ciliates was highest (~25%) (Figure 13).

### *Significance*

This year of intensive sampling of the plankton in Vancouver Lake in 2009, when compared with our previous results from 2008, has allowed us to document several important trends in the variability of their abundance, composition and distribution over the annual cycle. On a seasonal basis in Vancouver Lake, like other temperate lakes in North America, the plankton taxonomic composition shifts rather consistently from diverse wintertime assemblages of eukaryotic algae (diatoms, chlorophytes, cryptophytes), protozoans (large dinoflagellates and ciliates), cladocerans (daphnids) and rotifers, to springtime, pre-bloom communities dominated by a smaller number of taxa including diatoms, cryptophytes, larval and juvenile stages of copepods and an increasing abundance of cyanobacteria. In 2009 a cyanobacteria bloom occurred beginning in late July and extended at least into October, dominated by *Aphanizomenon flos-aquae*, as well as smaller peaks of chlorophyte and cryptophyte algae. Potential grazers such as ciliates, copepods and rotifers also reached maximal abundances in association with the cyanobacteria bloom. By November the plankton community returned to the diverse assemblage characteristic of winter.

Dilution experiments to determine algal growth rates and protozoan grazing rates over the full course of the 2009 cyanobacteria bloom demonstrated the dynamic nature of the balance between these rate processes. In spring algal growth rates were moderate, but were balanced by protozoan grazing rates. In mid-summer, just prior to the 2009 bloom period, a complicated set of grazer interactions may have contributed to the observation of negative protozoan grazing rates, which likely influenced conditions that allowed for a dramatic increase in cyanobacteria abundance that occurred in late July. Notably, while algal growth rates were high during the bloom, grazing rates of both protozoans and metazoan zooplankton (copepods) were also elevated at that time, such that overall grazing impact (% of the algal population consumed by predators per day) was consistently large, particularly on non-cyanobacteria taxa, and likely substantially influenced both the magnitude and composition of the bloom.

The experimental work supported by the Water Research Center in 2009 has allowed us to begin to quantify some of the trophic interactions among the plankton in Vancouver Lake that the on-going assessment of population abundance and composition has suggested may be important. Based on thte bloom cycle during 2009, it is clear that both protozoan and zooplankton grazers have the capacity to significantly consume cyanobacteria and algae, and at various stages of the bloom may have a strong enough grazing impact on particular groups to limit their standing stocks. These results will need to be combined with other food web studies (especially those targeted on higher trophic levels) to provide a more explicit set of predictions about when grazing impacts may be strongest, and will help to inform the discussion of whether managing the Lake to maximize these impacts (e.g., via biomanipulation) as a means to control cyanobacteria blooms is a viable option.

The results of these experiments in Vancouver Lake will also have broad implications for other lakes in Washington as well as shallow, temperate lakes around the globe. That is, quantifying intrinsic growth rates for cyanobacteria and grazing rates of both small (protozoan) and large (zooplankton) consumers under a range of environmental conditions will be useful to managers as they make critical decisions about appropriate measures to reduce or control these blooms. For instance, if cyanobacteria growth rates are consistently high, efforts to limit nutrient loading may be most effective; conversely, if grazing rates are consistently low or variable, then biological manipulation approaches that enhance grazer populations and communities may prove to be more useful. These kinds of management decisions would be impractical without empirical data to support one approach over another.

***Other significant activities:***

**Ms. Tammy Lee**, a master's degree candidate at Washington State University Vancouver was supported for one semester by this project as a Graduate Research Assistant, which allowed her to focus on the microscopic analyses of the protist plankton and cyanobacteria from Vancouver Lake in 2009, and to begin the statistical analyses of how environmental variables influence protist abundance and rate processes. Ms. Lee is being supervised jointly by Dr. Stephen Bollens and Dr. Gretchen Rollwagen-Bollens, and is expected to complete her thesis research in late 2010.

We intend to report the results of this proposed research in a variety of ways. First, in July 2009 we will be submitting a **manuscript for publication** to *Freshwater Biology*, a premier peer-reviewed journal widely read by freshwater ecologists and biologists, as well as managers. Second we will prepare and submit a report in August 2009 to Clark County, WA, Department of Public Works outlining the major findings that may inform decision-making for managing nutrient input and/or biological controls for Vancouver Lake. Finally, we expect to present our results at one or more **national or international scientific conferences** in late 2010 or early 2011.

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# Influence of Large Wood Addition on Nitrogen Transformations at the Surface water/groundwater interface

## Basic Information

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|---|---|
| **Title:** | Influence of Large Wood Addition on Nitrogen Transformations at the Surface water/groundwater interface |
| **Project Number:** | 2009WA265B |
| **Start Date:** | 3/1/2009 |
| **End Date:** | 2/28/2010 |
| **Funding Source:** | 104B |
| **Congressional District:** | Washington 4th |
| **Research Category:** | Water Quality |
| **Focus Category:** | Ecology, Groundwater, Nutrients |
| **Descriptors:** | None |
| **Principal Investigators:** | Clay Porter Arango, Carey Alice Gazis |

## Publications

1. Duke, Paul, 2011, Impact of Large Woody Debris on Nitrification in Taneum Creek, Ellensburg, WA, MS Thesis, Department of Biological Sciences, Central Washington University, Ellensburg, Washington. (In preparation)
2. Bishop, Tiffany, 2011, The Influence of Large Wood Addition on the Hyporheic Zone: An Evaluation of a Stream Restoration Practice on Taneum Creek in Ellensburg, WA, MS Thesis, Resource Management Program, Central Washington University, Ellensburg, Washington. (In Preparation)
3. Duke, P., C. Arango, P. James, and H. Pinkart, 2010, Impact of Large Woody Debris on Nitrification in Taneum Creek, Ellensburg, WA: Preliminary Findings, Symposium on University Research and Creative Expression, Ellensburg, Washington, www.cwu.edu/source/abstracts.php.

## 1. Problem and Research Objectives

The Yakima Basin historically supported 500,000 to 900,000 anadromous fish. Today, fish runs in the Yakima Basin have declined from a variety of well-documented land use practices including beaver removal, livestock grazing, logging, and agriculture. These land use activities have collectively denuded riparian vegetation, reduced wood recruitment to the channel, and controlled and diverted streamflow, thus decreasing stream habitat complexity, reducing instream flow, and decreasing water quality. In the Yakima River Basin, steelhead trout are listed as threatened under the Endangered Species Act, and local, state, tribal, and federal entities have undertaken a major effort to stabilize, restore, and enhance anadromous fish runs by improving habitat conditions.

Ecologists have long recognized the valuable role that large wood plays in stream ecosystems by retaining sediment and organic matter, increasing habitat diversity, and slowing stream flow to promote surface water/groundwater interaction, which in turn increases bank and floodplain water storage to improve late season base flow. Therefore, efforts to restore anadromous fish populations often include addition of large wood to streams that have had little wood recruitment due to historic land use practices. Although wood addition is commonplace in stream restoration, there are surprisingly few measurements of how large wood addition changes shallow hyporheic and floodplain hyporheic storage of water. Similarly, we know of no studies that have examined how changes in surface/groundwater interaction after wood addition alter water chemistry by changing rates of biogeochemical nutrient transformations in the shallow hyporheic zone. Our research will: <u>1) provide empirical measurements of how large wood addition changes surface/groundwater interaction in a stream reach</u>, and <u>2) quantify how large wood addition alter nitrogen dynamics in a stream reach.</u>

## 2. Methodology

<u>General Study Design:</u> Our study takes place in Taneum Creek, Kittitas County, Washington, and our study reach is in the vicinity of a large stream restoration effort coordinated by The Yakama Nation. We are implementing a BACI study design (Before-After Control-Impact) by utilizing an upstream control reach paired with a downstream treatment reach where added wood was expected to lodge. Pre-treatment data were collected in 2009 at approximately 1-2 week intervals and for 5 different sampling times before the wood addition. Although we planned on studying the stream before and after wood addition in a single summer, the Yakama Nation could not add wood to the stream until November 2009 due to unforeseen logistical constraints. Because of high flows in autumn, we were unable to make our post-wood addition measurements in 2009. Therefore, we asked for and received a no-cost extension until August 2010 to complete our post-wood addition analysis. Our revised plan is to study the effect of the wood addition beginning in summer 2010 after the spring flow pulse recedes. Our post-treatment measurements will take place at 1-2 week intervals 5-7 times in the upstream control and downstream treatment reaches. The following paragraphs describe the methods and their relationship to the objectives, with specific goals noted within each objective.

<u>Objective 1, Goal 1: Quantify surfacewater/groundwater interaction</u>

To provide empirical measurements of how wood changes surfacewater/groundwater interaction, we mapped the spatial distribution of vertical hydraulic exchange (i.e., upwelling/downwelling) in relation to current channel form. We performed a field survey to identify areas of upwelling and downwelling using perforated pipes to measure vertical hydraulic gradient (Valett et al. 1990). We have monitored temperature at the sites with the strongest vertical hydraulic gradient. We will repeat these measurements this summer to quantify changes in hyporheic exchange as a result of wood addition. Additionally, we plan on slug tests along floodplain hyporheic flow paths to quantify hydraulic conductivity, and we will install wells along the floodplain hyporheic flow paths to measure changes in nutrient chemistry in the floodplain aquifer.

Objective 1, Goal 2: Quantify transient storage

We quantified transient storage before wood addition to measure the dynamic capacity of the channel to store water. Transient storage represents the amount of water stored dynamically in the stream channel in eddies, pools, and in the shallow hyporheic zone. We used short-term (~ 1 h) releases of a conservative tracer (i.e., rhodamine WT) to measure the hydraulic properties of the stream, and we will use OTIS-P to quantify the size of the transient storage zone (Runkel 1998). Input for the OTIS Model is the observed concentration of a conservative tracer, pumped at a known rate in the stream and measured at a single downstream location. The model estimates transient storage parameters (size of the transient storage zone, and rate of exchange into and out of the transient storage zone, among others) by simulating results of the conservative tracer in a model of one-dimensional transport coupled with groundwater and transient storage exchange. We will also calculate channel friction (Darcy-Weinbach friction factor; Harvey et al. 2003) as an estimate of hydrologic retention. We will repeat these measurements this summer to understand how wood addition changed transient storage.

Objective 2, Goal 1: Measure whole-stream nitrogen cycling

We measured whole-stream ammonium and nitrate uptake using short-term enrichments (Webster and Valett 2006), a standard method to quantify stream nutrient cycling. A nutrient is pumped with a conservative tracer (e.g., rhodamine WT) at a constant, known rate into the stream. When the stream reaches a new equilibrium concentration, determined by measuring rhodamine WT concentration at the most downstream point, water samples are taken at 6-10 stations at known distances downstream from the pump. Concentration of the nutrient will decline downstream due to biological uptake and dilution whereas concentration of the conservative tracer will decline only due to dilution. The natural log transformed ratios of the nutrient and the conservative tracer at each station are plotted against distance of the station downstream from the pump. The data should plot as a simple linear regression, and the per meter uptake rate ($m^{-1}$) of the nutrient is represented as the slope of the regression line. Using the per meter uptake rate, we can calculate the areal uptake rate ($mg\ m^{-2}\ h^{-1}$) and the mass transfer coefficient (velocity a nutrient travels toward the stream bed: $mm\ min^{-1}$), both of which measure different aspects of stream nutrient cycling; the areal uptake rate represents the mass of nutrients taken up by a representative unit area in the stream in a given time whereas the mass transfer coefficient represents the biotic demand for a nutrient relative to the nutrient concentration. Using the same short-term nutrient enrichment experiments, we collected samples to estimate whole-stream nitrification. The observed longitudinal profile of nitrate concentration in these samples will be compared to a two-compartment model (observed ammonium and nitrate concentrations in stream water during a release of ammonium and a conservative trace) to estimate nitrification rates as in Mulholland et al. 2001.

Objective 2, Goal 2: Estimate sediment nitrification and respiration

We sampled stream sediments by removing the upper layer of cobbles and collecting a sediment core from the saturated zone. We took water samples to measure net nitrification as nitrate accumulation in chambers incubated in situ with hyporheic water for 2-4 hours (Jones et al. 1995). We measured changes in dissolved organic matter mineralization in the same samples by measuring respiration as the decline in oxygen throughout the incubation (Jones et al. 1995). Respiration is a key response variable because it can control ammonium production, which is in turn related to nitrification rate. After measuring nitrification rates in the sediments, we can compare these rates to whole-stream nitrification to allow us to determine whether whole-stream or hyporheic nitrification is a greater source of nitrate to the stream channel.

Overall Status: We collected our pre-treatment samples in summer 2009 and have performed many of the calculations. Wood was added in November 2009 (Figure 1). The ion chromatograph has been receiving heavy use by other users, and we are scheduled to run the $NO_3^-$ samples in the coming month. As such we are unable to report whole-stream nitrate uptake values or whole-stream or sediment nitrification rates. We intend to perform our post treatment sample collection and analysis in summer 2010.

**Figure 1.** Wood added in Nov 2009 should move into the study reach (250 m downstream) on the spring flow pulse.

### 3. Principal Findings and Significance

Surfacewater/groundwater interaction

Pretreatment data indicate multiple mid-channel upwelling and downwelling zones in the upstream and downstream reaches. Downwelling zones appear to be related to transitions between pools or glides and riffles, and upwelling zones often occur downstream of floodplain channels that flow during large spates (Figure 2). However, sometimes upwelling and downwelling may appear in close proximity (<50 cm apart). If wood adds geomorphic complexity in the treatment reach (contingent upon the wood flowing into the treatment reach), we anticipate finding a close relationship between channel complexity and increased surfacewater/groundwater interaction. Furthermore, we identified a partially connected channel newly formed by the winter 2009 flood, and we are studying changes in upwelling and downwelling patterns as the channel continues to develop. Finally, we plan on expanding our view of surface/groundwater interaction by enlarging our scope of study. To accomplish this we will study paleochannel flow paths and floodplain channels in order to estimate travel time through the floodplain hyporheic zone.

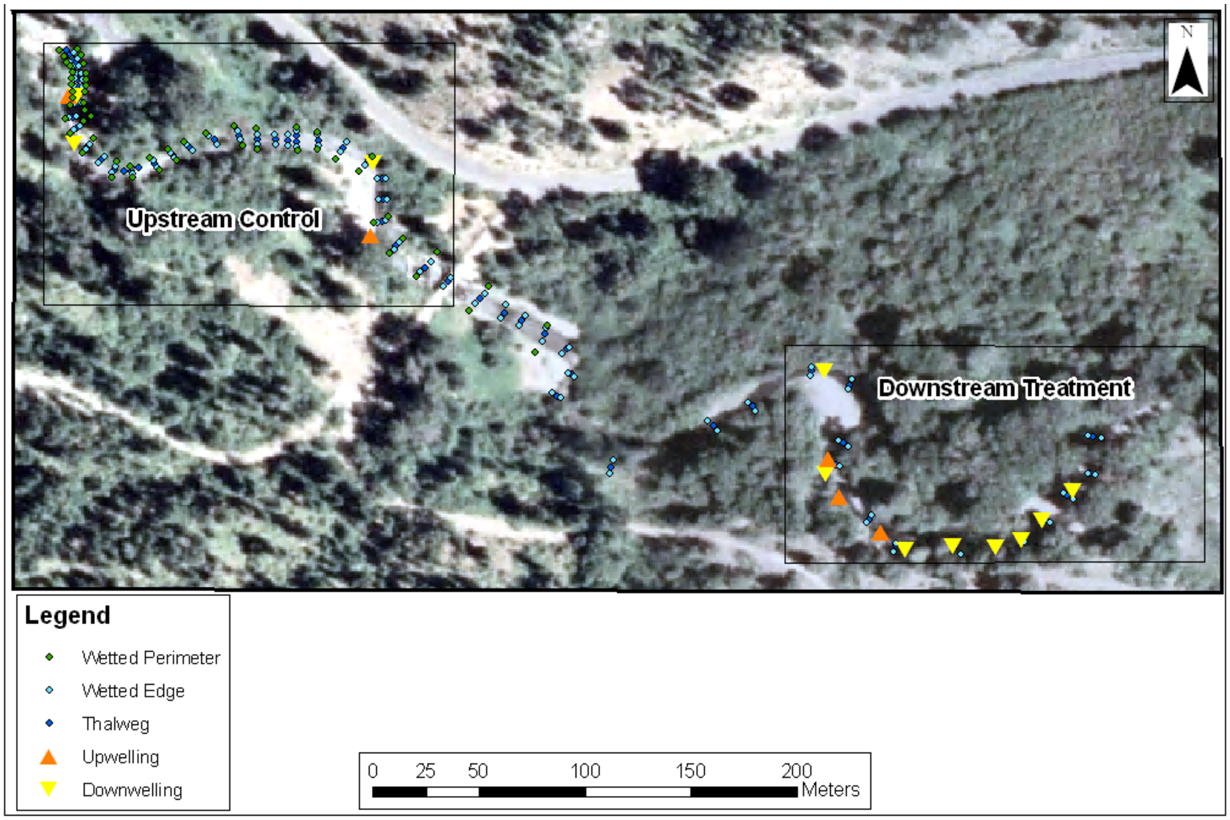


**Figure 2.** Spatial pattern of upwelling and downwelling in the upstream control and downstream treatment reaches.

<u>Transient Storage</u>

Our channel hydraulic data have not yet been analyzed using the OTIS-P model, but we can examine the conservative tracer releases and observe differences in transient storage between the upstream and downstream reach. Based on the sharper gradients in tracer concentration with time, the upstream control reach appears to have less transient storage than the downstream treatment reach prior to wood addition (Figure 3). Differences in transient storage prior to wood addition indicate hydraulic differences between the two reaches, which may be caused by differences in large wood density in the two reaches (Figure 4). The upstream reach has wood levels that are an order of magnitude below average for our region, whereas the downstream is somewhat below the average level (>4 $m^3$ $100^{-2}$; Cordova et al. 2007).

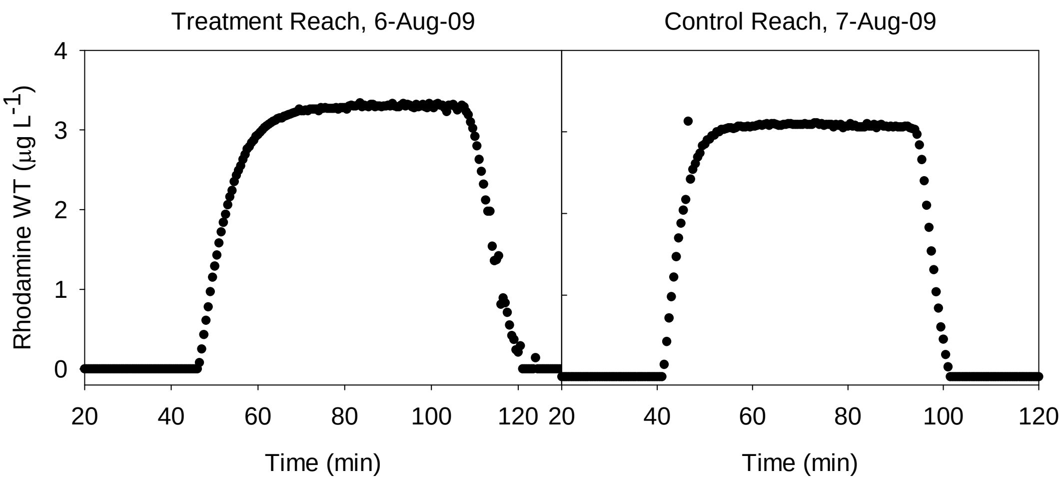


**Figure 3.** Conservative tracer profiles in the upstream control and downstream treatment reach. Transient storage is indicated by a less boxy shape as the curve reaches plateau and returns to baseline. These pre-treatment data suggest that the downstream reach has more transient storage than the upstream reach.

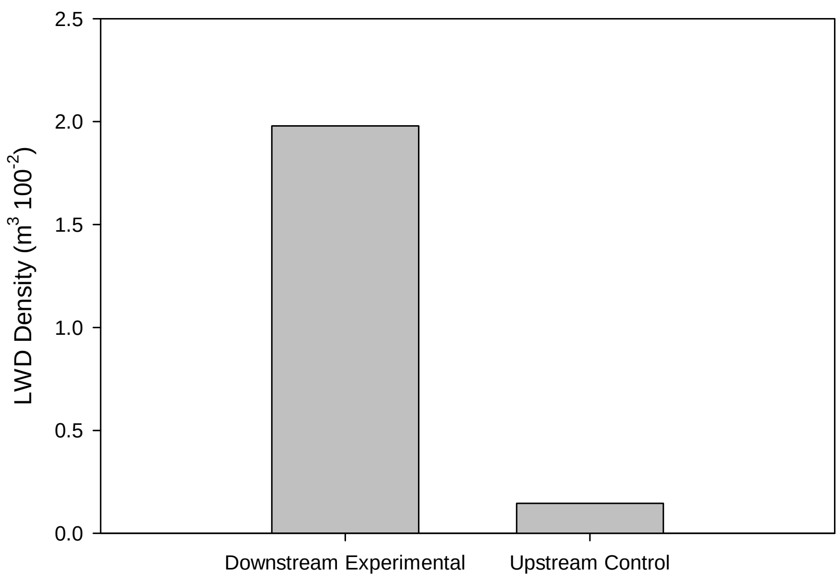


**Figure 4.** The downstream reach has more wood than the upstream reach prior to the experimental wood addition.

Whole-stream nitrogen cycling

To date our data focus on ammonium characteristics between the upstream and downstream reaches. Although ammonium concentrations are very low in both reaches and generally track each other through time (Figure 5), the upstream reach has significantly higher concentration than the downstream reach (rmANOVA, p<<0.001).

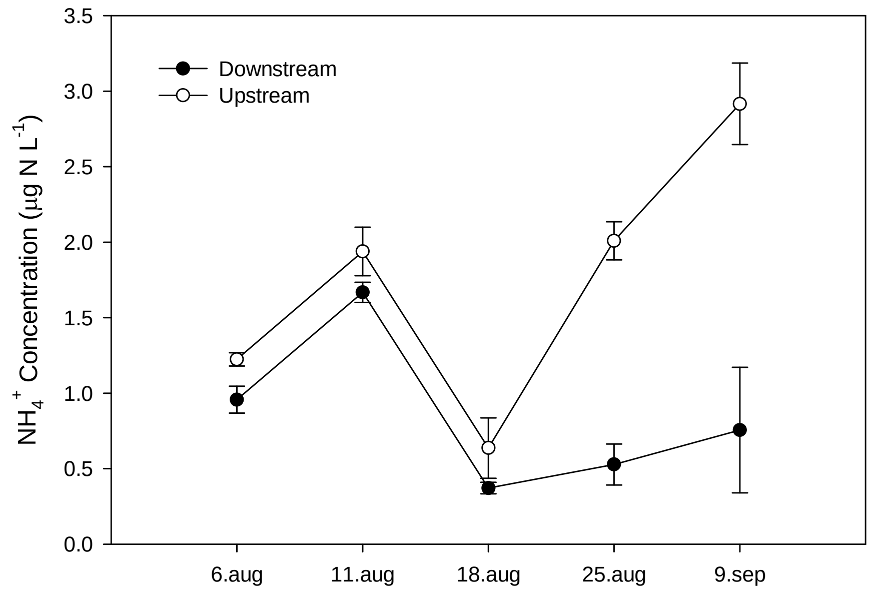


**Figure 5.** The upstream control reach had significantly higher ammonium concentration during the pre-treatment study.

Despite the significant differences in ammonium concentration, the pre-treatment whole-stream ammonium demand (i.e., $V_f$) did not differ between the reaches (paired *t*-test, p=0.161) (Figure 6), and other metrics of nutrient spiraling were not significantly different ($S_w$, paired *t*-test, p=0.113; and *U*, paired *t*-test, p=0.908).

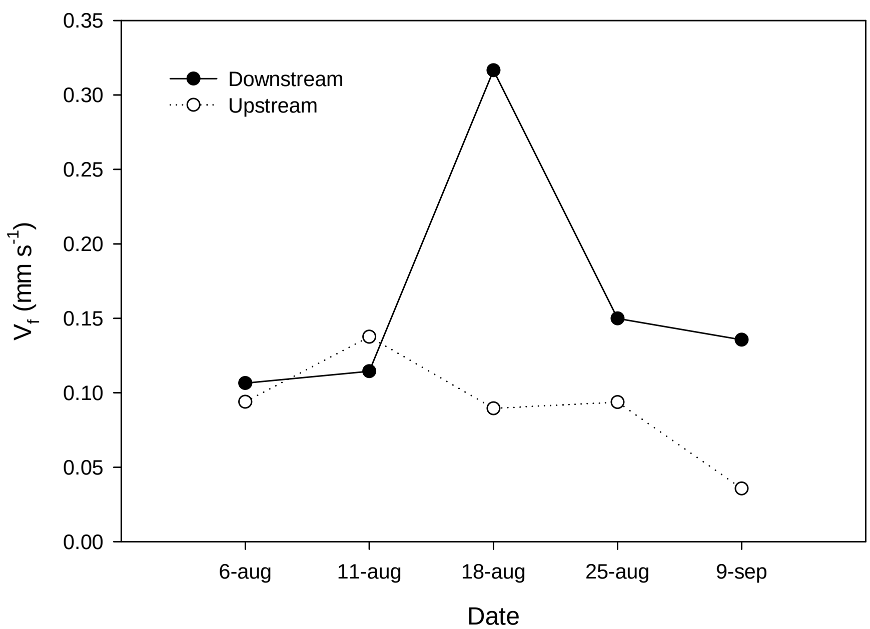


**Figure 6.** Pre-treatment biotic ammonium demand did not differ between study reaches.

<u>Sediment nitrification and respiration</u>

As stated previously, we have not had access to the IC to run nitrate samples, therefore we can only report sediment respiration rates (Figure 7), which did not vary between reaches (rmANOVA, p>0.05).

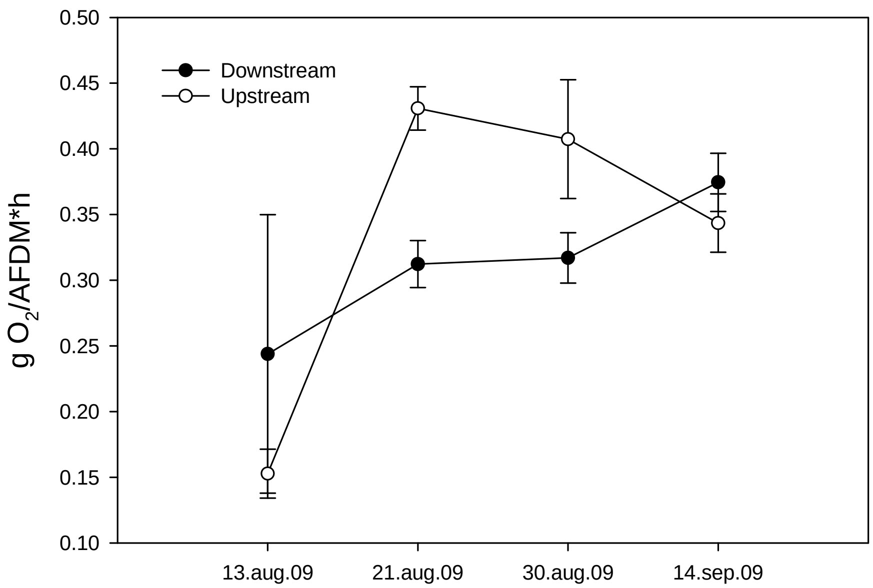


**Figure 7.** Pre-treatment sediment respiration rates did not differ between reaches.

## 4. Summary

Due to logistical constraints, the Yakama Nation did not add wood to the stream until November 2009, which precluded post-treatment sampling until summer 2010. Wood was added above the study site, and depending on peak discharge during the spring melt, the added wood may or may not flow into the study site. Overall, the reaches we chose to study appear to be good statistical replicates. The only significant difference we observed was higher ammonium concentration in the upstream reach, but there was no corresponding difference in stream nutrient cycling parameters. Transient storage may also be significantly greater in the downstream reach, perhaps due to much higher wood density prior to the wood addition. Two graduate students, Tiffany Bishop and Paul Duke, are working in this site on their thesis projects. Post-treatment sampling will occur in summer 2010, beginning in mid-June or when base flow conditions ensue, and sample analysis should be complete by the end of summer 2010.

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# Information Transfer Program Introduction

Outreach and Education are critically important components of the State of Washington Water Research Center mission. As agency and stakeholders struggle to comprehend important decisions facing water resources, it is essential that they receive unbiased information. The primary goal is to facilitate information exchange by providing opportunities for combining the academic work of research universities in the state with potential users and water stakeholders. This process occurs through a variety of activities, formal and informal, that raise the visibility of university research results throughout the Pacific Northwest. Federal, state and local agencies, non-governmental organizations, watershed groups, and concerned citizens are in need of interpreted science that can be applied to solving the regions water problems. The SWWRC makes substantial efforts to facilitate this process. The items described in the following Information Transfer Report constitute the core of the technology transfer activities.

# Information Transfer

## Basic Information

| | |
|---|---|
| **Title:** | Information Transfer |
| **Project Number:** | 2005WA114B |
| **Start Date:** | 3/1/2009 |
| **End Date:** | 2/28/2010 |
| **Funding Source:** | 104B |
| **Congressional District:** | Washington 5th |
| **Research Category:** | Not Applicable |
| **Focus Category:** | Education, Management and Planning, None |
| **Descriptors:** | Outreach, Information Transfer |
| **Principal Investigators:** | Michael Ernest Barber |

## Publications


1. Barber, M. and B. Bower, 2006, Evaluating Diversion Alternatives Affecting Environmental Flows and Temperatures, Presentation at UCOWR/NIWR Annual Conference, Increasing Fresh Water Supplies, Santa Fe, New Mexico.
2. Simmons,R., M. Barber, and J. Dobrowloski, 2006, Washington State University - Providing Solutions to Critical Water Issues, National Association of State Land Grant Universities and Colleges, NASULGC Science Exhibit on the Hill, Washington, D.C.
3. Barber, M.E., A. Hossain, J.J. Covert, and G.J. Gregory, 2009, Augmentation of Seasonal Low Stream Flows by Artificial Recharge in the Spokane Valley-Rathdrum Prairie Aquifer of Idaho and Washington. Hydrogeology Journal, Vol 17, pp 1459-1470.
4. Barber, M.E., February 2010, Interstate Groundwater Quantity Issues between Idaho and Washington, USDA Land Grant and Sea Grant National Water Conference, Hilton Head, South Carolina.
5. Barber, M.E. and Z. Al-Houri, July 2009, Frozen Soil Impacts on Stormwater Infiltration Treatment BMP Designs, 2009 UCOWR/NIWR Annual Conference, Urban Water Management: Issues and Opportunities, Chicago, Illinois.
6. Nelson, S., M.E. Barber, and D. Yonge, July 2009, Infiltration Pond Design Considerations for Cold Weather Conditions, 2009 UCOWR/NIWR Annual Conference, Urban Water Management: Issues and Opportunities, Chicago, Illinois.
7. Barber, M.E., R. Mahler, and J. Adam, June 2009, Climate Change and Western Prior Appropriation Water Laws in the United States: Compatible or Conflict?, Water Policy 2009, Joint Conference of APLU and ICA, Prague, Czech Republic.
8. Mahler, R. and M.E. Barber, June 2009, Water Policy Challenges in the Pacific Northwest Region of the USA, Poster Presentation, Water Policy 2009, Joint Conference of APLU and ICA, Prague, Czech Republic.
9. Al-Houri, Z. and M. Barber, March 2009, Frozen Soil Impacts on Stormwater Infiltration Treatment BMP Designs, Lessons from Continuity and Change in the Fourth International Polar Year Symposium, Inland Northwest Research Alliance, Fairbanks, Alaska.
10. Siegenthaler, M. and M.E. Barber, March 2009, Sustainability Issues Involving Stormwater and Highways, Road Builder s Clinic, Coeur d Alene, Idaho.

In order to achieve the goals outlined in the introduction, the following information transfer activities were conducted. It is important to recognize that several of these activities are highly leveraged with activities related to other research projects being conducted by the SWWRC. Nevertheless, without some support from the program, these activities would not be possible or as frequent.

Continued funding for a USDA-CSREES grant was received. The project helps to coordinate research and extension activities of the Water Research Institutes and Extension Services in Alaska, Idaho, Oregon, and Washington with US EPA Region 10 and the NRCS. Six meetings are held each year and communication between researchers, extension faculty, and government agencies is improved considerably by the activity. This project also provides some of the funding that the SWWRC leverages for support of a biennial water conference related to an emerging theme as identified by a regional steering committee. Planning and conducting of the November 2009 conference involving venue selection, call for abstract development, and other related activities was accomplished. Once again, this was a highly successful conference drawing over 200 local decision makers from around the region and works as an excellent avenue for showcasing SWWRC research efforts. Student competition in the poster session helped promote the education goal of the Center. A student competition showcased several SWWRC projects.

SWWRC co-sponsored the Palouse Basin Water Summit; a local event attracting stakeholders and concerned citizens from the bi-state watershed (ID and WA). Participants learn about water conservation, efforts to quantify groundwater resources, and other critical aspects of local watershed planning and management.

Director Michael Barber attended the NIWR meeting in Washington, DC to interact with other directors from around the country. He also attended a UCOWR meeting in Chicago, IL to attend a NIWR Board meeting and present an oral presentation on work done at WSU. At the invitation of the New Mexico Water Institute, he also gave a presentation at their international conference on transboundary water issues.

SWWRC sponsored a mini-retreat for water resources research attended by the WSU Vice President for Research and over a dozen water-related faculty. The goal of the retreat was to educate the upper administration regarding expertise and identify future research initiatives that were vital to the state and region. We also funded a workshop with King County staff and WSU researchers to explore funding opportunities at the local level. The Center also sponsored a graduate seminar on water resources and will continue to look for opportunities to expand these efforts.

We continued to actively participate in a strategic regional surface water initiative funded by the Department of Energy through the Inland Northwest Research Alliance (INRA). The project involves the Water Institutes and other researchers at the Universities of Alaska, Idaho, Utah State and Washington State, as well as other regional universities (Boise State, Idaho State, Montana, and Montana State). The project involves bi-monthly conference calls aimed at establishing a regional needs assessment (recently completed) and coordinating research and education programs integrating water science, policy, and decision making. The project recently took on a task of developing a regional water data portal called “ICEWATER” modeled after the NSF HIS system to allow data sharing.

Maintaining and updating our web site is a continuous process. This is an important avenue for us to present information about the activities of the Center and the research faculty in the state as well as news and events, research reports, and opportunities for research funding. We currently have all our research reports available for download via PDF format allowing for greater access and utilization of study results.

# USGS Summer Intern Program

None.

| Student Support | | | | | |
|---|---|---|---|---|---|
| **Category** | **Section 104 Base Grant** | **Section 104 NCGP Award** | **NIWR-USGS Internship** | **Supplemental Awards** | **Total** |
| **Undergraduate** | 1 | 0 | 0 | 0 | 1 |
| **Masters** | 4 | 1 | 0 | 0 | 5 |
| **Ph.D.** | 0 | 4 | 0 | 0 | 4 |
| **Post-Doc.** | 0 | 0 | 0 | 0 | 0 |
| **Total** | 5 | 5 | 0 | 0 | 10 |

# Notable Awards and Achievements

2006WA180G: Awarded the American Water Resources Association "Outstanding Chapter of the Year," for work on linking research, education, and societal outreach. 2006. (PI Steinemann was faculty adviser to AWRA student chapter, and four students in chapter were supported by USGS grant.)

Dr. Michael Barber, Director of the State of Washington Water Research Center and Professor of Civil and Environmental Engineering, was elected to serve as President of the Universities Council on Water Resources (UCOWR). UCOWR has over 90 member universities and organizations throughout the world whose main objectives are to: 1) facilitate water-related education at all levels, 2) promote meaningful research and technology transfer on contemporary and emerging water resources issues, 3) compile and disseminate information on water problems and solutions, and 4) inform the public about water issues with the objective of promoting informed decisions at all levels of society.

# Publications from Prior Years